

UC-NRLF



\$C 113 170





BINDING
PREP. DIV.
CAT. P.O.B.
PHYSICS

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

PUBLICATION NUMBER FOUR OF THE
ERNEST KEMPTON ADAMS FUND FOR PHYSICAL RESEARCH
ESTABLISHED DECEMBER 17TH, 1904

RESEARCHES IN PHYSICAL OPTICS

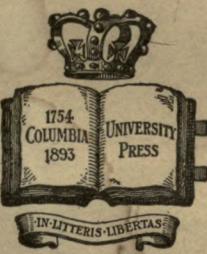
WITH ESPECIAL REFERENCE TO
THE RADIATION OF ELECTRONS

PART I

BY

R. W. WOOD, LL.D.

PROFESSOR OF EXPERIMENTAL PHYSICS IN THE JOHNS HOPKINS UNIVERSITY
AND ADAMS RESEARCH FELLOW OF COLUMBIA UNIVERSITY



NEW YORK
COLUMBIA UNIVERSITY PRESS
1913

PHYSICS

PRESS OF
THE NEW ERA PRINTING COMPANY
LANCASTER, PA.

On the seventeenth day of December, nineteen hundred and four, Edward Dean Adams, of New York, established in Columbia University "The Ernest Kempton Adams Fund for Physical Research" as a memorial to his son, Ernest Kempton Adams, who received the degrees of Electrical Engineering in 1897 and Master of Arts in 1898, and who devoted his life to scientific research. The income of this fund is, by the terms of the deed of gift, to be devoted to the maintenance of a research fellowship and to the publication and distribution of the results of scientific research on the part of the fellow. A generous interpretation of the terms of the deed on the part of Mr. Adams and of the Trustees of the University has made it possible to issue and distribute a limited number of copies of the following lectures as a publication of the Ernest Kempton Adams Fund.

Previous Publications
of the
Ernest Kempton Adams Fund for Physical Research:

Number one. **Fields of Force.** By VILHELM FRIMAN KOREN BJERKNES. A course of lectures delivered at Columbia University, 1905-6.

Number two. **The Theory of Electrons and its Application to the Phenomena of Light and Radiant Heat.** By H. A. LORENTZ. A course of lectures delivered at Columbia University, 1906-7.

Number four. **Graphical Methods.** By C. RUNGE. A course of lectures delivered at Columbia University, 1909-10.

PREFACE.

The researches described in the following pages have been completed during the academic year 1911-1912, and deal for the most part with problems relating to the radiation of electrons.

In the first two papers I have discussed the resonance spectra of iodine, the work having been done in part in the laboratory of the Royal Institution, London, and in part in Baltimore, and in my laboratory at East Hampton. The investigation is by no means finished at the present time, and the work will be carried on during the coming year, the prospects of arriving at some very definite conclusions regarding the genesis of these very remarkable spectra appearing very bright. The third paper treats of the scattering, absorption, and reflection of monochromatic ultraviolet light, by the vapor of mercury at room temperature, and at a pressure of only 0.001 mm. This investigation may be regarded as finished, though several interesting side lines have developed, which require following up. The phenomena treated of are wholly new for the most part, and have never before been investigated experimentally. The results which have been obtained throw a good deal of new light upon the action of molecules upon light which is in exact synchronism with the natural period of vibration of the electron.

The remaining papers deal in part with related subjects, and in part with other branches of physical optics, and it has seemed best to include them in the present publication, as they were all carried on during the tenure of the fellowship.

I am under great obligation to the publishers of the Philosophical Magazine, The Astrophysical Journal and the Physikalische Zeitschrift, for assistance given in the illustration of the papers. Generous aid has also been received from the Rumford fund of the American Academy.

R. W. WOOD.

BALTIMORE,
November, 1912.

TABLE OF CONTENTS.

	Page.
1. The Resonance Spectra of Iodine Vapor and their Transformation into Band Spectra by Gases of the Helium Group.....	1
2. Resonance Spectra of Iodine Vapor by Multiplex Excitation.....	26
3. The Selective Scattering, Absorption, and Reflection of Light by Resonating Gas Molecules.....	42
4. The Selective Dispersion of Mercury Vapor.....	75
5. Resonance Experiments with Very Long Heat Waves.....	83
6. Diffraction Gratings with Controlled Groove Form, and Anomalous Distribution of Intensity.....	88
7. Nickeled Glass Reflectors for Astronomical Photography in the Ultraviolet.....	96
8. Selective Reflection from the Moon's Surface and Lunar Petrography.....	103
9. Preliminary Note on the Electron Atmospheres of Metals.....	114
10. The Satellites of the Mercury Lines.....	122
11. The Imprisonment of Radiation by Internal Reflection and its Liberation.....	129

NO. 1.

THE RESONANCE SPECTRA OF IODINE AND THEIR
TRANSFORMATION INTO BAND SPECTRA BY
GASES OF THE HELIUM GROUP.

PLATES 1, 2 AND 2A.

INTRODUCTION.

GENERAL NATURE OF RESONANCE SPECTRA.

The discovery of resonance spectra which I announced in 1904, and their study, which I have outlined in a series of papers which have appeared in the Philosophical Magazine since that date and the present time, have furnished a new method of attacking the problem of the nature of molecular radiation. Resonance spectra arise in the following manner. The vapors of sodium, potassium, iodine and certain other elements and compounds, such as the oxides of nitrogen, exhibit absorption spectra consisting of thousands of very fine lines grouped together with more or less regularity into bands, which in certain cases appear to be arranged according to a certain law as has been observed by Deslandres and others. Some of these vapors when illuminated with a powerful beam of white light become luminous (*i. e.*, fluoresce) and if we examine the emitted light with a spectroscope we find that the spectrum, roughly speaking, is the complement of the absorption spectrum, that is, the dark lines of the one are replaced by bright lines in the other. The simplest way of explaining this phenomenon would be to assume that each absorption line removes from the incident beam the frequency corresponding to its own, and reëmits this frequency laterally in all directions. This explanation was found to be insufficient, for experiment showed that if sodium vapor was illuminated with light comprised between rather narrow limits

NO. 1.

THE RESONANCE SPECTRA OF IODINE AND THEIR
TRANSFORMATION INTO BAND SPECTRA BY
GASES OF THE HELIUM GROUP.

PLATES 1, 2 AND 2A.

INTRODUCTION.

GENERAL NATURE OF RESONANCE SPECTRA.

The discovery of resonance spectra which I announced in 1904, and their study, which I have outlined in a series of papers which have appeared in the Philosophical Magazine since that date and the present time, have furnished a new method of attacking the problem of the nature of molecular radiation. Resonance spectra arise in the following manner. The vapors of sodium, potassium, iodine and certain other elements and compounds, such as the oxides of nitrogen, exhibit absorption spectra consisting of thousands of very fine lines grouped together with more or less regularity into bands, which in certain cases appear to be arranged according to a certain law as has been observed by Deslandres and others. Some of these vapors when illuminated with a powerful beam of white light become luminous (*i. e.*, fluoresce) and if we examine the emitted light with a spectroscope we find that the spectrum, roughly speaking, is the complement of the absorption spectrum, that is, the dark lines of the one are replaced by bright lines in the other. The simplest way of explaining this phenomenon would be to assume that each absorption line removes from the incident beam the frequency corresponding to its own, and reëmits this frequency laterally in all directions. This explanation was found to be insufficient, for experiment showed that if sodium vapor was illuminated with light comprised between rather narrow limits

of wave-length, cut out from a continuous spectrum, the fluorescent spectrum covered practically the same spectrum range as when white light was employed. The experiment was then tried of illuminating the vapor with monochromatic light obtained from a metallic arc, allowing only light corresponding to one of the spectrum lines to reach the vapor. The spectroscope now showed that the vapor was emitting a series of isolated bright lines spaced at nearly equal distances along a normal spectrum. One line coincided in position with that of the exciting line, from one to three appeared on the short wave-length side of it, and the remainder, to the number of ten or a dozen, on the long wave-length side. To spectra excited in this way I gave the name resonance spectra, since they appeared to be originated by a resonance of the absorbing molecule for a definite frequency, the energy abstracted from the incident beam being for the most part distributed among other frequencies by a mechanism within the molecule, the nature of which has not been definitely determined up to the present time, though two or three promising hypotheses have been offered, as I shall show presently. The study of these resonance spectra was attended with great experimental difficulties, since the intensity of the light emitted under monochromatic stimulation was so faint that exposures varying from eight to twenty hours were necessary. For this length of time it was necessary to keep the metallic arc, which requires constant attention, burning steadily. Moreover the vapor of the metal had to be kept away from the glass walls of the vessel which contained it, involving further difficulties, which it is not necessary to go into, but which will be found described in my earlier papers. In the autumn of 1910 I discovered the resonance spectrum of iodine vapor excited by the monochromatic radiations from the mercury arc burning in a quartz tube, and at once the study of these spectra became very simple, since these lamps can be run continuously several thousand hours without attention, and the iodine vapor can be enclosed in glass bulbs or tubes, which require no heating, as the most favorable density of the

vapor turned out to be that which obtains at room temperature. During the year of study which I have given to the subject many new and interesting phenomena have come to light, and some of the circumstances which I found difficulty in explaining in the case of sodium vapor appear to have been satisfactorily cleared up.

Among the more remarkable of the new phenomena may be mentioned the striking circumstance that if the iodine vapor exists in an atmosphere of helium at a pressure of only 2 or 3 mm. instead of in a high vacuum, the complete band spectrum, very similar to that excited by white light, appears in addition to the resonance spectrum, while at a pressure of 8 or 10 mm. the resonance spectrum disappears entirely and is replaced by the band spectrum. This remarkable effect of molecular collisions was studied in collaboration with J. Franck early in year 1911, and has been the subject of further study during the year following. The circumstance that the light making up the resonance spectra was partially polarized also came to light, and gives us important additional information as to what is going on within the radiating molecule. In the course of a very extended study of resonance spectra with which I have been engaged off and on for the past seven years, I have come to the conclusion that no very great advance could be made until some method was devised for varying the wave-length of the exciting light by very small amounts.

In the previous work the spectra excited by a large number of widely separated wave-lengths have been studied, but no very general conclusion as to the nature of the molecular mechanism could be drawn from the accumulated material.

During the past winter I have advanced a step in the right direction and have made a very good beginning on the work which I have always hoped would be possible.

Some very astonishing results have been obtained, which throw a good deal of light on certain points which I never felt able to explain in the course of the work on sodium vapor.

I have found, for example, that the resonance spectrum of iodine is quite different when excited by the green line of the Cooper-Hewitt mercury lamp (commercial glass lamp) from the resonance spectrum excited by the *same line* from the mercury arc in quartz (high temperature arc), in other words the resonance spectrum suffers profound changes when small changes occur in the structure of the exciting line. In all of the previous work I have assumed that only one of the hundreds of absorption lines was operated upon by the exciting line, though in one or two cases I ventured the hypothesis that the exciting line might be broad enough to act upon two absorption lines simultaneously (see paper by R. W. Wood and F. E. Hackett on the resonance spectra of sodium photographed with the concave grating, *Astro-physical Journal*, 1909).

The complexity of the iodine absorption spectrum has been greatly underestimated. With any grating of moderate power it appears to be completely resolved, though some of the lines appear broader than others. I find, however, that with every increase in the resolving power that I bring to bear, more structure comes into view. The elaborate maps and tables of wave-lengths which have been published from time to time are absolutely worthless. I have made a study of this absorption spectrum only in the vicinity of the mercury emission lines which I have employed for exciting the resonance spectra but this study has demonstrated what I have for many years suspected, that tables of wave-lengths of spectra of this type are of no more value than a carefully prepared table of the weights of the individual grains in a cupful of sand.

I have employed the highest resolving power that has ever been brought to bear upon the spectrum and it is still not completely resolved. As an illustration of the amount of value to be attached to tables of wave-lengths and maps I may mention that I have found seven sharp and cleanly resolved absorption lines of iodine *within* the green mercury line emitted by the quartz mercury arc, the light of the mercury lamp being trans-

mitted through iodine vapor before reaching the spectroscope. This group of seven lines is represented by a single line only on Hasselberg's great map of the iodine spectrum. Fourteen absorption lines were found in one of the yellow mercury lines and twelve in the other. When therefore we excite the resonance spectra by one or the other of these lines, from seven to fourteen different frequencies may respond to what we might be tempted to call monochromatic excitation.

It becomes at once clear why a small change in the distribution of the intensity in the exciting line or in its structure may modify the resonance spectrum.

Excitation by lines which are broad enough to excite a number of adjacent frequencies I have accordingly named *multiplex excitation* to distinguish it from excitation by lines so narrow that they cover a single absorption line only. I have even succeeded in modifying the line structure of the exciting line by the use of ray filters which remove certain frequencies from it; for example, by passing the green light from the mercury arc through bromine vapor before allowing it to enter the iodine vapor we can produce a change in the resonance spectrum excited by the green mercury line. The changes produced in this way are very interesting, and the same method could without doubt be applied to the study of the resonance spectra of sodium, by filtering the light through iodine or bromine vapor before allowing the selected line to stimulate the vapor of sodium.

In my earlier paper I expressed the belief that much more could be learned from the study of the resonance spectra of iodine than was the case with sodium, since the vapor is much easier to handle. This belief has been amply justified, and I have so improved the method of investigation that I can now secure, with an exposure of ten minutes, a far better photograph of the resonance spectrum than was obtained with an exposure of 24 hours in the first experiments which I made in collaboration with Dr. Franek in Berlin in 1910. I shall take up in this paper the subject of the resonance spectra as a whole, photographed

with my large three-prism spectrograph, and in the one following pass to the more interesting subject of the structure of the resonance lines themselves as affected by the structure of the exciting line. This part of the work was done with the concave grating. The study of the absorption of the iodine for the frequencies falling within the spectral range covered by the exciting lines owing to their finite width, was done first with a six-inch plane grating in the fourth order spectrum, used in conjunction with a spectrometer of considerably over two meters focus, and subsequently with a 40-foot spectrograph which I installed in my East Hampton laboratory in August of the present year (1912).

APPARATUS AND METHODS.

Thus far I have employed only the mercury arc for the excitation of the vapor, for I have found that sufficient variety could be obtained with this source alone to make possible a very complete study of the genesis of resonance spectra. It has moreover an advantage over most other sources of monochromatic light in that it is extremely brilliant and can be kept running continuously for an almost indefinite length of time. I have employed two different types of lamp: a commercial Cooper-Hewitt burning in a long glass tube at a comparatively low temperature, and a very powerful Westinghouse Cooper-Hewitt lamp (quartz) such as is used for the sterilization of water on a large scale. This lamp is of almost insupportable brilliancy, and many times more powerful than the small Heraeus lamps with which I have worked previously. I have already had it in operation over 2,000 hours and so far as I can see it is in as good order as when first made. It operates at 220 volts and takes 7 amperes when first started, the current dropping gradually during the first ten minutes of operation becoming stationary at about 3.5 amperes, the lamp then being red hot. I had my lamp constructed so that it could be used end-on if necessary, which has proved advantageous in the case of another investigation with which I have been

occupied. The lamp is mounted in a large wooden box, furnished with a number of apertures, so that two or three investigations can be made with it simultaneously. Over one of these apertures is fitted the large lantern condenser of 25 cm. in diameter, which forms an image of the mercury arc along the axis of the tube containing the iodine vapor. I find it advantageous to make these tubes rather larger than these which I used at first. I now make them about 40 cm. long and 4 or 5 cm. in diameter, with one end blown out into a bulb 4 cm. in diameter. It is important to get this bulb as clear and free from striæ as possible and above all things not to have a drop of glass at the center. This can be accomplished by drawing out the tube sideways in closing it preliminary to blowing it out. The other end of the tube is drawn down to a diameter of about 5 mm. and a thick-walled constriction made close to the large tube for sealing after exhaustion. Before making the constriction a few small crystals of iodine are introduced into the tube (the tube must be freed from moisture), which is then put in communication with a Gaede or other mercurial pump and thoroughly exhausted. I usually keep the Gaede pump in operation for ten minutes, as the gas passes but slowly through the capillary at low pressures. The tube is used end-on of course, the iodine vapor being highly luminous along the axis of the tube where the image of the horizontal mercury arc is focused. The intensity can be further increased by means of a strip of looking glass placed close to the wall of the tube which reflects the rays back through the vapor. In some cases I have silvered the outer surface of the iodine tube along the side opposite to that through which the rays enter. This acts as a concave cylindrical reflector and focuses the rays back again at the center of the tube. If it is desired to stimulate the vapor by the light of the Cooper-Hewitt arc in glass, the same tube can be used mounted along side of the lamp and as close to it as possible, no lens being used. The entire mass of iodine vapor within the tube becomes luminous, though the intrinsic intensity is much less than with the quartz arc,

perhaps one third as great. The mirror should of course be used in this case. On looking down the axis of the tube through the bulb the yellowish fluorescent light is seen, and the spectroscope exhibits the discontinuous resonance spectrum composed of isolated bright lines. If the light from the carbon arc, or still better sunlight, is concentrated at the center of the tube as near the bulb as possible, the characteristic band spectrum excited by white light appears. The ease with which this experiment can be performed makes it of interest in view of the importance of resonance and band spectra in connection with the theory of the radiation of electrons. With these improvements in the arrangement of the apparatus, it is now possible to show the resonance spectrum to a class in optics by means of a commercial Cooper-Hewitt lamp (in glass) and a small pocket spectroscope.

If helium is available, a second tube may be prepared for showing the transformation of the resonance into the band spectrum. The tube is prepared as before, and the gas introduced until the manometer indicates a pressure of about 5 mm., after which it is sealed off from the pump. These tubes keep indefinitely, require no heating, and may be set up for exhibition in two or three minutes. The only advantage of the quartz mercury arcs used in the present investigation lies in the greater intrinsic brilliancy of the light.

The use of glass bulbs for the study of the fluorescence has been discontinued, as it has been found that tubes similar to those described above give greater brilliancy and far less trouble resulting from reflection of the light of the arc from the walls. It will be found advantageous to wrap the end of the tube with black cloth; this gives us a dark background against which the fluorescent light stands out. A round-bottomed flask, 20 cm. in diameter, containing a small crystal of iodine, drawn down at the neck, highly exhausted and sealed makes a very nice piece of lecture apparatus for showing the fluorescence of the vapor. The light from the carbon arc is focused at the center of the bulb by the condenser of a projection lantern, preferably arranged to

throw a vertical beam, as in this way disturbing reflections from the walls are avoided. The cone of fluorescent light is bright enough to be seen from the back of the largest lecture hall.

The present investigation was commenced in the laboratory of the Royal Institution, which was placed at my disposal through the courtesy of Sir James Dewar, the investigation of many points being made possible by the giant Nicol prisms, condensing-lenses, and other apparatus not usually found in physical laboratories. I am also under great obligation to Mr. Twyman, of the firm of Adam Hilger & Son, who placed echelons, spectrographs, and other optical apparatus at my disposal, and to Mr. Kenneth Mees, who very kindly lent me his small prism spectrograph, with which the first photographs were made.

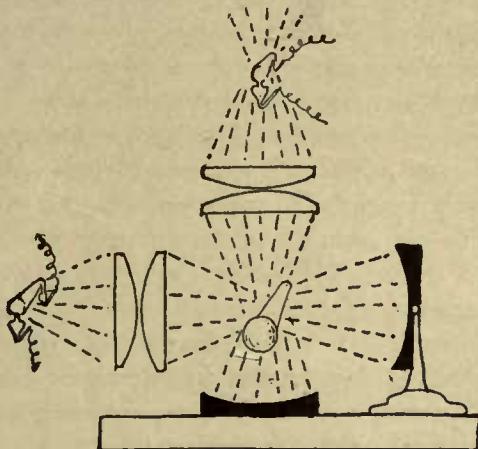


FIG. 1.

Thanks to improvements made in the method of illuminating the vapor, it was possible to obtain the resonance spectrum with sufficient brilliancy to permit of its examination with the echelon, which was thought to be of great importance in connection with the proposed examination for a possible Zeeman effect. I searched for the effect in the laboratory of M. Cotton in Paris

with a large Weiss electromagnet, but at that time it was impossible to obtain the spectrum with a brilliancy sufficient to permit of its examination with any spectroscope of high resolving power, and nothing was accomplished. More recent investigations have shown however that the echelon is not adapted to the study of the resonance lines.

The arrangement of the apparatus built up at the Royal Institution is shown in Fig. 1. Two large quartz mercury arc-lamps made by the Westinghouse Cooper-Hewitt Co., of London, which I have found to be much more powerful than any lamps which I have used previously, were used for illuminating the vapor. One of these was mounted above the tube, and the rays, after having been brought to a focus at the center of the tube by a condensing lens of 25 cm. aperture, were returned to the same focus by means of a large concave mirror placed below the tube (which was at the center of curvature of the mirror). One lamp was thus made to do the work of two. The other lamp was mounted to one side of the tube with a similar arrangement of lens and mirror. The mercury arc-lamps were about 12 cm. in length, and their images formed along the axis of the iodine tube by condensing lenses and mirrors were of the same dimensions.

This arrangement appears to give us very nearly the maximum amount of illumination possible, the only improvement which I have been able to think of being an iodine tube completely surrounded by a mercury arc burning in a long closely-wound spiral tube of quartz. I have also had constructed a glass mercury arc with the iodine tube passing axially down its center, but I have not yet succeeded in getting it to work very well. Dr. Peter Cooper-Hewitt has more recently made for me a very fine lamp of this description which I have not yet had time to try. With the arrangement just described, I found that I could get a fully exposed photograph of the resonance spectrum with a Hilger wave-length spectrograph in less than two hours, whereas in the earlier experiments exposures varying from 18 to 24 hours

were necessary. The greatly increased brilliancy of the fluorescence which is obtained by the use of a tube can be ascribed to the following circumstance. It was found that when a large bulb was used, as in the earlier experiments, if the light was returned to the focus by a concave mirror placed behind the bulb, the cone of fluorescent light produced by this reflected beam was so faint that it contributed very little to the total intensity. This resulted from the absorption of the exciting frequencies by the iodine vapor. It is obvious that if we employ a bulb and focus the light at its center, much of the available energy is lost before the rays come to a focus. This difficulty is avoided by the use of a tube, since the exciting rays traverse only the small volume of iodine vapor which is under observation.

The photographs taken in London were made with a small Hilger spectrograph, and the wave-lengths as determined from them are not very accurate. On my return to Baltimore in the autumn of 1911 all of the previous work was repeated.

The iodine tube was brought close up to the slit of the spectrograph, no lens being used on account of the large size of the luminous spot. The resonance spectra were photographed with a prism spectrograph furnished with three very large flint glass prisms 12 cm. high and a Cooke portrait lens of about 1 meter focus. Higher dispersion was obtained by photographing the spectra with a concave grating of 2 meters radius of curvature, very bright in the first order, ruled with 15,000 lines to the inch. The absorption spectrum was studied visually in the fourth order spectrum of a six-inch plane grating with the large spectrometer previously mentioned. The resolving power was 300,000 and the grating easily separated lines only 0.03 Ångström unit apart. Photographs were made with this grating but they did not show as much fine detail as could be observed visually and measured with the eye-piece micrometer, on account of small tremors which are never wholly absent in Baltimore, even late at night. These difficulties were overcome in the case of the 40-foot spectrograph, which will be described in the following paper.

The fine groups of absorption lines of iodine which fall within the range covered by the green and two yellow emission lines of the mercury arc were first observed and studied with a large echelon grating, but subsequent work with the large plane grating showed that the results yielded by the echelon had been wrongly interpreted due to the overlapping of different orders, and they will not be further discussed, as it was at once apparent that a six-inch plane grating in the fourth order spectrum gave equal resolving power, sharper definition, and results about the interpretation of which there could be no doubt. In each case the spectrum of a neon tube was photographed on the same plate superposed on the resonance spectrum, the length of the slit being reduced, however, to make their identification certain. In some cases the iron arc was impressed upon the plate as well, as the neon tube gives but few lines in the green region, while very rich in lines in the yellow, orange and red. In the case of the grating photographs the comparison spectrum was not superposed on the resonance spectrum, the usual method of a rotating slot being employed.

THE RESONANCE SPECTRA.

As I have indicated in previous communications the resonance spectrum of the iodine vapor excited to luminosity by the light of the mercury arc consists of three superposed series of nearly equidistant lines, one excited by the green line, the other two by the yellow lines. I have succeeded in separating the former from the two latter by the interposition of suitable absorbing screens between the mercury lamp and the iodine tube, and in the discussion of the results I shall take up the series separately.

If we photograph the resonance spectra with a spectrograph giving fairly high dispersion we find that the lines which form the series excited by the green line are in reality close doublets, accompanied by fainter companions, which however do not appear except on fully exposed plates. Neglecting these companions for the present we will consider the series of doublets.

The extent of this series has been somewhat extended since the earlier investigation and it now consists of twenty-five members (all double), two of which are missing. Some of the others are very faint. Certain lines were found to be missing in the case of the resonance spectra of sodium vapor, and this peculiarity is probably characteristic of all resonance spectra. Dunoyer has made the suggestion that each line in the series originates from a special configuration of an aggregate of two or more sodium atoms or aggregates of sodium and the residual gas in the tube, and that the missing lines correspond to aggregates which are unstable or which cannot exist. This is an interesting hypothesis, and we are at once reminded of the equilibrium figures formed by floating magnets, some of which are very unstable, while others cannot exist at all.

My first idea regarding the series of doublets was that a close pair of absorption lines were excited by the green line and that the spacing of the lines in the two series thus originated was slightly different, the two series starting at the same point (the green mercury line). This would, however, give us a series of doublets with constantly increasing separation, whereas the observed separation is very nearly constant (about 2 Ångström units). The law governing the spacing of the doublets is not the same as that which obtains in the case of the resonance spectra of sodium, in which case I have found that the lines are spaced at very nearly equal distances along a normal spectrum. This makes the wave-length differences constant, but the law is by no means strictly followed, and matters become only worse if we take frequency differences. In the case of iodine the distance between the lines increases steadily, as we pass towards the region of longer wave-lengths, but if we take the frequencies, or what amounts to the same thing, the reciprocals of the wave-lengths we find that the frequency differences are approximately constant. They are not strictly so, however, and it seems possible that the departures may be the result of slight perturbations which modify the periods.

The wave-lengths were determined from photographs made on Wratten and Wainwright films, with a concave grating of 15,000 lines to the inch and a radius of curvature of six feet. The wave-lengths to which they are referred are the most recent values given for the neon lines by Priest, of the Bureau of Standards (interferometer determinations). In the following table I have given the wave-length differences, the reciprocals of the wave-lengths (frequencies) and the frequency differences. The first six lines (starred) were determined from photographs made with the three-prism spectrograph, as I have not yet obtained a record of them with the grating. The values can be considered correct to two or three tenths of an Ångström unit I think, and represent the position of the centers of the doublets, for the prism spectrograph barely resolved them.

I have used only the first members of the doublets in calculating the wave-length differences, frequencies, etc.

The last two lines form a wide doublet, and are very faint; they appeared on one plate only and I am not sure about fitting them into the series. I have taken the *second* member in this case in making the calculations, as it fits the series better. The 5,397 line is not a doublet, neither can I find any indication that the 5,460.7 line (the primary line) is double, though it is accompanied by faint companions, like all the other doublets, as we shall see presently. I took great precautions to prevent any diffused light from the mercury arc from getting into the spectrograph, but it is just possible that this line is really emitted by the iodine vapor as a doublet, the gap between the components being filled up by stray light from the arc, which would be the case if the doublet were symmetrical about the green mercury line. More recent work shows that this is not the case.

As is apparent from the table the frequency differences increase a trifle in passing from one end of the spectrum to the other.

The photographs of the entire resonance spectrum taken with the concave grating were made with a very fine slit and were not fully exposed even with a 24-hour exposure. The lines were

DOUBLET SERIES EXCITED BY GREEN Hg LINE (COOPER-HEWITT LAMP).

	Dif.	Frequencies.	Freq. Dif.
7,005.5*	91	142,850	1,880
6,909.5*	88.5	144,730	1,880
6,821.0*	88.6	146,610	1,930
6,732.4*	87.4	148,540	1,950
6,645.0*?	84.3	150,490	
6,560.73		152,420	(1,930)
6,558.4			
Missing	82.2		1,960
6,396.30		156,340	
6,394.3	79.66		1,970
6,316.64		158,310	
6,314.4	79.05		2,010
6,237.59		160,320	
6,235.7	76.92		2,000
6,160.67		162,320	
6,158.8			
Missing	74.94		2,025
6,010.79		166,370	
6,009.1	72.85		2,040
5,937.94		168,410	
5,935.0	72.06		2,070
5,865.88		170,480	
5,864.8	69.77		2,050
5,796.11		172,530	
5,794.6	69.28		2,090
5,736.83		174,620	
5,725.3	67.86		2,090
5,658.97		176,710	
5,657.4	66.90		2,113
5,592.07		178,823	
5,589.8	65.17		2,107
5,526.90		180,930	
5,525.2	66.16		2,195
5,460.74 (Hg)		183,125	2,158
5,397.13	63.61	185,283	
5,342.63	59.50		2,067
5,337.63		187,350	

beautifully sharp, and served admirably for measurement, but they are scarcely strong enough to bear reproduction. A portion of the spectrum however was taken on an isochromatric plate which is much more sensitive in the yellow and this plate is reproduced

on Plate 2, spectrum *F*. The lines are rather broad on this plate and the fainter companions of the doublets come out as well; these will be discussed presently. Spectrum *G* was made of the vapor excited by the light of the quartz mercury arc, while *F* was made with the glass Cooper-Hewitt lamp. The resonance spectra will be found to be quite different in some respects. On Plate 1 will be found the resonance spectra photographed with the large prism spectrograph. All of the spectra, with the exception of *A* are reproduced as negatives, as the lines come out better. On this plate *A* and *B* are the spectra excited by the Cooper-Hewitt lamp, *C*, by the Westinghouse quartz lamp, *D*, the resonance spectrum excited by the green line acting alone (quartz lamp) and *E* the spectrum excited by the two yellow lines acting alone. Spectrum *D* is the series of doublets which we have just discussed, though they are not resolved on the plates which are reproduced.

Spectrum *D* was made by interposing a glass tank containing a solution of neodymium chloride between the mercury arc and the iodine tube, the solution absorbing the yellow light. In the case of *E* a solution of eosine was used which absorbed the green light.

We will now consider the series excited by the two yellow lines. The more refrangible of the two yellow lines excites a series of doublets when we employ the Cooper-Hewitt arc. These can be seen in spectrum *B*. If the quartz arc is used (spectrum *C*) we find triplets in place of the doublets, the middle component being very strong, and the two outer ones weak. This is due to the fact that we have a different distribution of intensity in the mercury exciting lines in the two cases. The wave-lengths given in the following table are determined from plates made with the Cooper-Hewitt lamp. Values starred were from plates made with the prism spectrograph.

The wave-length differences are not as regular as in the case of the series excited by the green line, and there is no point in calculating the reciprocals or frequencies in this case.

SERIES EXCITED BY THE TWO YELLOW MERCURY LINES.

6,547. *	75.	6,659.2	81.2
6,540.2*		6,578.0	
6,472. *	78.6	6,571.7	80.5
6,466.4*		6,487.5	
6,388.4*	82.	6,481.0	
6,384. *		6,406.0	81.5
6,306.5*	82.	6,404.2	
6,299.5*		6,327.8	78.2
6,224.53	77.2	6,324.6	84.9
6,219.84		6,342.93	
6,147.30	77.	6,240.24	
6,143.		6,163.62	80.
Missing		6,153.40	
5,993.28	74.4	6,092. *	77.
5,988.21		6,086.5 *	
5,918.90	72.5	6,083. *	76.5
5,914.02		6,010. *	
5,846.36	76.7	5,931.24	79.
5,841.29		5,865.	68.2
5,769.60 Hg		5,790.66 Hg	74.3

The distances between the components of the doublets excited by the more refrangible of the two yellow lines varies from 4.5 to 7 Ångström units, which in itself indicates that the series spacing cannot be uniform.

The series excited by the yellow line of longer wave-length is still more lawless! Some lines are single, some double, and one triple.

TRANSFORMATION OF RESONANCE SPECTRA INTO BAND SPECTRA
BY GASES OF THE HELIUM GROUP.

The introduction of helium into the iodine vacuum-bulb results, as has been pointed out, in the development of the band spectrum similar to that which we have when we excite the vapor with white light.

Photographs of the band spectrum, with the resonance lines superposed, excited by the light of the mercury arc when the iodine vapor is mixed with helium at various pressures, are re-

produced on Plate 2. Spectrum *H* is a portion of the resonance spectrum between the green mercury line—to the left—and the two yellow lines—to the right—the iodine being in a high vacuum. Spectrum *I* shows the effect of introducing helium at 2 millimeters pressure and spectrum *J* the effect of helium at 10 mm. pressure. The other gases of the helium group behave in the same way and I have recently found that the band spectrum can be brought out by the presence of air at one or two millimeters, though the intensity of the fluorescence is enormously weakened and long exposures are required. It is my plan to investigate this side of the subject during the coming winter. One of my tubes which originally was highly exhausted, and showed only the resonance spectrum, after long use showed traces of the band spectrum. I have therefore prepared some tubes containing only iodine vapor, that is, no solid crystals, to see whether prolonged illumination eventually destroys the vapor. It is of course a very delicate matter to speculate about the result of any such experiments, and sufficient data are not yet at hand to make their discussion worth while. The band spectrum appears faintly when the helium is at a pressure of a millimeter or less, and as the helium pressure increases, the intensity of the band spectrum increases, while that of the resonance spectrum decreases, the total amount of emitted light remaining about the same, however. It is still an open question whether both spectra are emitted simultaneously by the same molecule. I am rather doubtful about this, for it seems more probable that when the helium is at a very low pressure, the band spectrum is emitted only by those molecules which at the moment happen to be within the sphere of influence of a helium molecule. It is possible that a momentary combination between a helium atom and one of iodine may exist either normally or under the action of light. Sir J. J. Thomson has found that such momentary combinations exist between atoms in vacuum-tubes developing canal rays, which would be considered impossible by the chemists. It would be extremely interesting to investigate the positive rays

excited in a mixture of helium and iodine by Thomson's very beautiful method.

It appeared to be of the greatest importance to investigate the behavior of the other gases of the helium group in this respect, for, as has been shown in a previous investigation by Wood and Franck, the commoner gases, hydrogen, nitrogen, oxygen, appeared at first to be without influence in developing the band spectrum, though I have recently observed it with a millimeter or two of air in the tube as stated above. Thanks to the kindness and interest of Sir William Ramsay and Professor Collie, the gases argon, neon, krypton, and xenon were placed at my disposal.

We will consider the behavior of the gases in the order of their molecular weight.

In helium, with a molecular weight of 4, at a pressure of 10 mm., the band spectrum is very strong and there is scarcely a trace of the resonance spectrum. In neon at the same pressure (weight 20) the resonance spectrum is relatively much stronger. This is partially in accord with the views expressed in a previous paper by Franck and Wood, regarding the relation between the affinity of a gas for electrons and its action in destroying fluorescence. According to the investigations of Franck neon has the smallest electron affinity of all the gases, less even than that of helium. According to our theory, if a gas has a strong affinity for electrons it destroys completely the emission of all of the fluorescing molecules which at the moment happen to be within the sphere of action of one of the gas molecules, without, however, affecting the nature of the radiation of the iodine molecules which at the moment happen to be outside of the sphere of action. This means that as the pressure of the gas is increased, more and more of the iodine molecules are within the sphere of action at any given moment and fewer and fewer of them emit light; the resonance spectrum therefore gradually fades away without any trace of the band spectrum appearing. In the case of a gas having small affinity for electrons, we find that we can

have it present at a relatively high pressure without any great reduction in the total amount of light emitted by the iodine, and that it operates in some manner, the nature of which we cannot at present surmise, in transferring the energy from the excited system of electrons to all of the other systems present in the molecule. The question now arises as to whether the efficiency of these gases in developing the band spectrum depends upon their molecular weight, or upon some other property. Neon is five times as heavy as helium, yet at the same pressure (10 mm.) the resonance spectrum is relatively much stronger.

We cannot be quite sure of the exact relations until photometric measurements have been made of the intensity of the resonance spectrum and the band spectrum of iodine in the gases of the helium group at different pressures. In argon, at 6 mm. pressure the total light emitted is much less than in neon and helium at 10 mm., but the resonance spectrum is stronger in proportion to the band spectrum than in the case of neon at 10 mm. In krypton (weight 83), at 1.7 mm. pressure the intensity of the emitted light is reduced to about $\frac{1}{2}$ of its original value and the spectroscope shows only the barest trace of the band spectrum, practically all of the light remaining localized in the resonance lines, as is the case with the common gases. In xenon (weight 130), at 1.5 mm. pressure the intensity is found reduced to about $\frac{1}{4}$ of its original value with no trace whatever of the band spectrum. Helium, the lightest of these rare gases, thus appears to be the most efficient in developing the band spectrum. I had expected to find neon more efficient than helium, for it has a smaller affinity for electrons according to Franck, and exhibits most remarkable electrical properties. Professor Collie showed me a tube about half a meter long containing neon at a pressure of an atmosphere and a half, through which the discharge of an induction-coil passed in preference to an alternative spark-gap in air of less than a centimeter arranged in multiple with the tube. In neon, however, the intensity of the emitted light is about the

same as in helium at the same pressure, and much more of it is localized in the resonance lines.

This matter requires a more careful investigation, for I was able to devote not more than the two or three days immediately preceding my departure from London to this part of the investigation.

POLARIZATION OF THE LIGHT IN RESONANCE SPECTRA.

The polarization of the light of fluorescent gases was discovered by the author more than three years ago (Phil. Mag., July, 1908). It was found to be much stronger in sodium and potassium than in iodine vapor. This subject has been taken up again, in view of its great importance in connection with the genesis of resonance spectra, and I now find that it is possible to obtain almost as strong polarization with iodine vapor as was formerly observed with sodium. This is probably due to the fact that in the earlier work very small glass bulbs were used, which quite possibly were insufficiently exhausted. In the case of the resonance spectra I never felt quite satisfied with my observations, though I obtained what I considered fair evidence that when the fluorescence was excited by polarized monochromatic light, the light was polarized in all of the lines of the resonance spectrum. This has been fully corroborated in the present work, by a method which admits of no doubt.

The percentage of polarization was first determined in the case of iodine vapor excited by polarized white light, by the same method used in the earlier investigation.

It was found that the Savart fringes could be destroyed by two glass plates at an angle of 43° , and by one glass plate at an angle of 56° , and the percentage of polarization comes out as 17 in each case. For sodium vapor I found 20 per cent. of polarization, or in the case of very rare vapor at a low temperature, as high as 30 per cent.

The polarization was easily observed when the fluorescence was excited by the mercury arc, the large glass bulb, 20 cm. in

diameter, used for the demonstration of the fluorescence before a large audience, being found best adapted to the work. The light from the arc was first rendered parallel by means of a large condenser, then passed through a Nicol prism of about 13 cm. aperture, and finally focused at the center of the bulb by a second condenser. A large Savart plate was mounted to one side of the bulb, and the fringes viewed through a second large nicol. It was first necessary to get rid of all reflections of polarized light from the walls of the bulb and room. This was accomplished by means of screens suitably placed, and a background of black velvet. To make sure that the fringes resulted wholly from the fluorescent iodine vapor, the wall of the bulb was touched with a bit of cotton soaked with liquid air. This immediately condensed the vapor, destroyed the fluorescence and all trace of the fringes, the background appearing perfectly black. It is of course necessary to get the bulb in such a position that none of the internal reflections comes from the region where the fringes are observed.

On Pl. 2a, Fig. 1, we have a photograph of the fluorescence of the vapor excited by the mercury arc without the nicols or Savart plate, and (Fig. 2) a photograph of the Savart fringes crossing the cone of fluorescent light. It was thought that possibly the percentage of polarization could be increased by reducing the density of the iodine vapor. The oblique plates by which the polarization was compensated were set at such an angle as to just cause the disappearance of the fringes, under which conditions any increment in the percentage of polarization would cause their reappearance.

The outside of the bulb was now touched with cotton soaked with liquid air, which caused a rapid condensation of the iodine vapor. The cone of fluorescent light faded gradually away, but the Savart fringes did not reappear, though the results obtained with sodium vapor made me think that at the lowest vapor densities consistent with visible fluorescence, increased polarization might be expected. Warming the bulb to increase the vapor

density above the value which it has at room temperature did not appear to decrease the amount of polarization, though the intensity of the fluorescence was considerably diminished.

The investigation of the polarization of the resonance lines was next investigated. This I regard as one of the most important points in the whole investigation, for if the bright lines excited by polarized monochromatic light are themselves polarized, it indicates that the directed motion passed over by the light-waves to the resonant electron is passed on as directed motion to the other electrons, or whatever the centers of emission of the bright lines of the resonance spectrum may be. The Savart fringes were formed as before, cutting vertically across the horizontal cone of fluorescent light excited by the polarized light from the mercury arc. A screen of black paper, perforated at its center with a horizontal aperture about 3 cm. in length by 2 mm. in width, was now mounted between the bulb and the Savart plate in such a position that the aperture covered the brightest part of the fluorescent cone. On looking through the analyzing Nicol the aperture was seen brightly illuminated except for the dark regions where it covered the Savart fringes. A direct-vision prism of high dispersion was now held before the eye, oriented in such a way as to give vertical dispersion. A vertical spectrum, or a series of images of the aperture corresponding to the brightest lines of the resonance spectrum, was clearly seen, and the fringes cut across all of these images (Fig. 2) and were quite as distinct in the images corresponding to wave-lengths not present in the mercury arc as in those due to light which was reemitted from the vapor without change of wave-length (resonance radiation). This method was far more satisfactory than the one employed for the same purpose in the case of sodium vapor, and gave results about which there could be no question. The addition of helium appears to diminish the per-

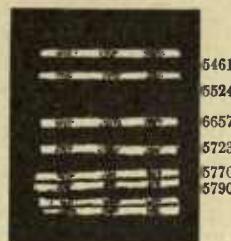


FIG. 2.

centage of polarization, for in the bulb containing helium at a pressure of 10 mm., the percentage of polarization was found to be only 13, against 17 when the iodine vapor was *in vacuo*. In helium at 10 mm. the resonance spectrum is completely replaced by the band spectrum, and the fact that polarization is still present indicates that the polarized vibration is passed over to the other electron systems.

RESONANCE SPECTRA WITH THE ECHELON.

Through the courtesy of Mr. Twyman, who placed a number of very fine echelons made by the Hilger Company at my disposal, I was able to make a preliminary study of the appearance of resonance spectra under high resolving power. The first inspection was very discouraging, for the width of the lines turned out to be as great as, or greater than, the distance between the orders.

It was at once observed, however, that this same condition existed in the case of the exciting radiations from the mercury arc, on account of the great density of the mercury vapor in the red-hot quartz tube. The mercury lamp was accordingly extinguished and allowed to cool off. On relighting the lamp, the fluorescence of the iodine vapor was at first too feeble to permit of observation with the echelon, but as it gradually brightened as the temperature and intensity of the mercury lamp increased, the lines appeared, and were observed distinctly narrower than the distance between the orders. Moreover, their width appeared to be the same as that of the exciting lines of the arc, which came out much stronger than the resonance lines on account of diffused light. As the arc lines widened, the resonance lines increased in width at the same rate, until they fused into a continuous band, due to the overlapping of orders. Calculation showed that the width of the lines when they were first observable in the echelon was of the order of 1/20th of the distance between the D lines.

The cause in the apparent width of the lines seen with the echelon will be seen in the following paper to be due to the fact

that we are dealing with groups of lines. Nothing is to be expected of observations made with this instrument.

I have succeeded in obtaining resonance spectra from iodine vapor with other monochromatic excitations, but have not yet studied them.

DESTRUCTION OF THE FLUORESCENCE BY TEMPERATURE.

It will be remembered that I found that the fluorescence of mercury vapor is destroyed by raising the temperature of the quartz flask with a blast lamp. The same thing is true of iodine, which, however, loses its luminosity at a temperature so low that the effect can be shown with a tube of soft glass heated with a small bunsen flame, the fluorescence disappearing at about the temperature at which the glass begins to soften.

There is an immense amount of work to be done with iodine, and if we are ever to learn anything about these enormously complicated absorption spectra, it is my belief that the subject must be attacked along the lines indicated in this paper. This recent work puts a new light on some of the results found with sodium vapor, which can now be repeated to advantage. In every case it will be essential to study the exciting line in connection with the absorption spectrum at the same point with a resolving power in the neighborhood of 300,000. In continuing the work I propose to have the exciting line under observation with an echelon or large grating throughout the exposure.

(Note added Nov., 1912.) This plan has proved to be of great advantage. The light from the quartz mercury arc, while exciting the iodine vapor, is watched with the large grating used in the 40-foot East Hampton spectrograph described in the following paper.

NO. 2.

RESONANCE SPECTRA OF IODINE WITH MULTIPLEX EXCITATION.

PLATES 2, 3, AND 4.

In the previous paper I have given a general treatment of the various phenomena observed in the case of iodine vapor rendered self-luminous by the absorption of light. In the study of the resonance spectra it has been shown that, what were at first thought to be single isolated lines, are in reality close groups of lines, each group consisting of a close doublet or triplet accompanied by fainter lines. While it is quite possible that even resonance lines originated by the excitation of a single absorption line, may be accompanied by fainter companions, there is no doubt but what, in the present case, the complicated groups result from the circumstance that the emission line, used for stimulating the vapor to fluorescence, is wide enough to cover a number of the absorption lines of the iodine vapor. Stimulation under these conditions I have named multiplex excitation, and the present paper will deal with a critical study of this subject, in so far as I have been able to carry it at the present time. The photographs obtained with the concave grating last winter showed that a very careful study of the absorption spectrum under the highest possible dispersion was necessary. It appeared necessary to study as well the intensity distribution in the lines used for exciting the vapor, and we will begin with a description of the instrument which I set up during the past summer for this purpose.

THE 40-FOOT SPECTROGRAPH.

The discovery of the satellite lines which accompany the resonance lines, and the change in their position and intensity

which resulted from changes in the distribution of the intensity within the exciting line made a careful photographic study of the absorption spectrum of the iodine and of the emission spectrum of the mercury arc much to be desired. I accordingly fitted up during the past summer a plane grating spectrograph of 12.5 meters focal length. As this spectrograph appears to be the largest and most powerful in the world, a description of the method of mounting may be of interest. The grating is a plane one ruled by Dr. Anderson on the 15,000 machine, and the photographs which I have taken with it of the iodine absorption spectrum show that it yields its full theoretical resolving power of 300,000 in the fourth order, which is bright enough to yield a fully exposed photograph of the solar spectrum with a very fine slit in three minutes, when used with a lens of 12.5 meters focus. My laboratory at East Hampton is in an old barn of very large size, and as temperature differences and striæ due to air currents can be better avoided by having the entire apparatus under cover, I first mounted the apparatus in the building. I soon found however that vibrations of the building due to wind, and probably expansion and contraction of its frame due to the changing position of the sun, made it very difficult to secure satisfactory photographs, though I occasionally obtained one showing full theoretical resolving power. I finally determined to mount the instrument entirely independent of the building, supporting the grating and the lens on a cast iron pier outside of the building, and the slit and plate holder on a similar pier sunk in the ground just inside the wall of my dark room. Not wishing to order a lens until I had tried out the instrument under the conditions prevailing at East Hampton (I had some fear of vibrations resulting from the surf on the beach a quarter of a mile distant) I borrowed through the courtesy of Professor Campbell and the regents of the University of California a very fine six inch achromatic lens of 40-foot focus. The pier, which carried this lens and the grating, I improvised from two six-inch water mains which were slightly damaged by last winter's

frost, and were to be had for the asking. The joints of these pipes had been ground together and the two were bolted together as when laid for service. The resulting pipe was sunk to a depth of six feet in the ground, and a triangular brass bracket from my junk heap, which had originally formed a truss on an old-fashioned support for a large reflecting telescope, was bolted to a bent piece of wrought iron, which was in turn bolted to the flange on the top of the water pipe. The cell of the lens was fastened to the brass triangle with adjusting screws in the usual manner. The grating was mounted on a circle, taken from an old spectrometer, which was turned by a worm gear. A bevel gear, removed from a discarded hand drill, was fastened to the worm, the small gear wheel being turned by a long rod, made by fastening four lengths of cheap brass-covered iron curtain rod together. This rod passed through the wall of the barn terminating in a wheel a little to one side of the plate holder and slit. When photographing with the apparatus the small gear wheel is thrown out of mesh with the large one by sliding a wooden support through which the rod passes a little to one side, the object being to prevent the transmission of vibrations from the grating house and the long wooden tube to the grating support.

The wooden tube, down which the light from the slit passes to the lens and grating and back again to the plate or eye-piece, was supported on posts and roofed over to prevent it from being heated by the sun. The end of the tube passes through the wall of the grating house but does not come in contact with the lens support. The plate holder and slit were supported on a shorter piece of water pipe, which passed through the floor of the laboratory without contact with it. The camera consisted of two wooden boxes, one sliding within the other (for focusing) joined to the end of the long tube with black cloth, which shut out the light but did not transmit vibrations. The long tube was made by nailing eight-inch boards together, and was painted black on the inside. Some trouble was given by spiders, which

built their webs at intervals along the tube, a difficulty which I surmounted by sending our pussy-cat through it, subsequently destroying the spiders with poisonous fumes.

The grating house was built with double walls, and shingled on the outside, the shingles being nailed to wooden strips so as to leave an air space between them and the roof. The iron pier was shielded from the wind by a wooden box built around it, which reached from the ground to the seven-inch hole in the floor of the grating house through which the pier passed without contact.

I have mentioned these details of construction to show that a somewhat elaborate apparatus can be put together out of odds and ends, without going to the expense of castings and machine work. A photograph of the entire structure, and the top of the pier and the grating and lens supports, before they were housed in, are reproduced on Plate 4. The apparatus has proved satisfactory in every way, the only trouble resulting from air currents which blow down the tube and stir up striæ. These give no trouble at night and are practically absent on calm days, but on windy days with hot sunshine, they impair the definition somewhat. The rest of the equipment which I installed for the work consisted of a heliostat for work with sunlight and a Cooper-Hewitt mercury rectifier which delivers 3.5 amperes at 220 volts for operating the mercury lamps. While this spectroscope does not equal in resolving power the most powerful echelons and plane parallel plates, I am of the opinion that the perfection of the grating, the circumstance that it is very bright in the fourth order, and the long focus of the lens, makes it second to no other instrument in the world capable of yielding a continuous spectrum. Lines in the bromine absorption spectrum separated by a distance of only .022 of an Ångström unit are clearly separated in the photographs, while the theoretical resolution is .018 A.U.

THE ABSORPTION SPECTRUM.

The absorption spectrum of iodine is made up of a large number of fluted bands, and resembles in its general appearance the

channeled absorption of sodium vapor, for in both cases the bands at the long wave-length end are quite regular in their appearance, while at the short wave-length end they become more or less confused. As I have already said the number of absorption lines, which collectively form the banded spectrum of iodine, has been greatly underestimated. Sunlight from the heliostat was passed through a large exhausted bulb containing a few small crystals of iodine and focused upon the slit of the instrument. The absorption spectrum seen under these conditions presented a most wonderful appearance, nearly the entire visible spectrum being filled with thousands of lines. As I have said I found seven sharp and beautifully resolved lines within the green emission line of mercury. The total width of the line was 0.4 A.E. and we have at this rate eighteen lines to the Ångström unit or about 36,000 lines in all. There were however groups containing lines much closer together than the seven lines just enumerated, which were still unresolved by the grating and numerous broad dark bands undoubtedly made up of unresolved lines. This circumstance together with the fact that the lines are much closer together in the red, orange and yellow region, makes me feel certain that there are upwards of 50,000 lines in this remarkable absorption spectrum.

The wave-lengths of the seven lines which were observed within the green mercury line (furnished by the quartz mercury arc) were very carefully measured with the eye-piece micrometer, with reference to the wave-lengths of the components of the mercury line seen with a low temperature arc.

They were subsequently measured from photographs taken with the 40-foot spectrograph, with reference to the main component of the green mercury line, which falls midway between two of the iodine absorption lines, and the wave-length of which is 5,460.7424.

The wave-lengths of the seven iodine absorption lines are as follows:

5,460.966
.910
.973
.873
.768
.716
.640
.579

As will be seen presently, the resonance spectra ought to be studied under equally high resolving power, but this is almost out of the question, on account of the comparative feebleness of the light. I have however obtained excellent photographs with a concave grating of six feet radius of curvature, and hope to do better in the autumn. The examination of the absorption spectrum under the highest dispersion possible is of interest in connection with the finite width of the lines due to the velocities of the molecules in the line of sight. They are at their best only when the iodine vapor is in a very high vacuum; the presence of air, even at rather low pressure, causes the lines to lose in sharpness, and eventually obliterates the finer ones. A portion of the absorption spectrum 8 Ång. units in width is reproduced on Plate 3, spectrum *W*, in coincidence with the corresponding portion of the spectrum from Hasselberg's map, enlarged to the same scale (spectrum *y*). The three broad lines on my photograph are solar lines, which appear on Hasselberg's map immediately above his spectrum. Hasselberg's map was prepared by hand from his table of measurements made from photographs taken with a grating of inferior power, the drawing being subsequently verified by comparison with the photograph. A comparison of the two shows that the lines in Hasselberg's map mean nothing at all, except that they indicate roughly the position of some of the groups of lines. Nevertheless he worked with iodine in vacuo under precisely similar conditions. A study of these two pictures cannot but furnish food for thought to astronomers working at the problem of the canals on Mars.

The group of seven lines which fall within the green mercury

line are enclosed with a bracket, and when it is remembered that the entire portion of the spectrum reproduced embraces a range of the spectrum not much greater than the distance which separates the D lines of sodium, the frightful complexity of these absorption spectra becomes evident.

I have examined the absorption spectrum of sodium with this very powerful apparatus and find that it is equally complex, the distance between the lines being about the same as in the case of iodine. Sodium however exhibits only a single faint line within the green mercury line, and as this appears only when the vapor has a considerable density, the mercury arc is incapable of stimulating this vapor to appreciable fluorescence.

The bromine absorption spectrum is reproduced in coincidence with that of iodine on the same plate (spectrum, *X*). Further reference will be made to this when I come to the subject of the use of bromine vapor as a ray filter, for modifying the intensity distribution in the green mercury line, and for the present I shall only draw attention to the somewhat suggestive circumstance that a large number of the lines in the two spectra coincide. From a rather hasty study of the original plate with a low power microscope (the photographs reproduced are threefold enlargements) I have come to the conclusion that there are more coincidences than can result from accident, a question which can doubtless be settled by the study of a wider range of the spectrum and a count of the percentage of coincidences with the spectra thrown out of wave-length coincidence by varying amounts. It appears to me that there may very possibly exist in the two elements identical systems of electrons, which give rise to similar frequencies in the two molecules. This is a point which I am studying at the present time. It may be well to point out that the iodine absorption spectrum seen with sunlight is far superior to the solar spectrum for testing large gratings.

STRUCTURE OF THE RESONANCE LINES UNDER HIGH RESOLVING POWER. MULTIPLEX EXCITATION.

If we examine under high resolving power the series of doublets excited by the green mercury line we find a remarkably complicated structure which appears to result from the circumstance that we are dealing with multiplex excitation. The spectra were photographed with a concave grating of six-foot radius ruled with 15,000 lines to the inch. The iodine tube was excited by the Cooper-Hewitt lamp and a portion of the photograph obtained in this way will be found reproduced on Plate 2, spectrum *F*. This same region excited by the quartz lamp will be found immediately below (spectrum *G*). It is quite apparent that the component lines which accompany the doublets are quite different in the two cases. Moreover in the latter photograph it will be found that the doublets are displaced toward the region of shorter wave-length with respect to those in the spectrum excited by the Cooper-Hewitt lamp. The difference between the two spectra is more clearly brought out by the drawing reproduced in Fig. 1, page 38, which was made from photographs obtained with a very fine slit, which are not suitable for reproduction. The component of the doublet which has the longer wave-length in the case of the quartz arc excitation is in coincidence with the component of shorter wave-length in the photograph obtained with the Cooper-Hewitt lamp, in which we find however a faint line exactly in coincidence with the other component of the doublet. What is more remarkable however is the absence of coincidence in the case of some of the fainter lines. The line at wave-length 5,461 is accompanied by fainter companions spaced in much the same way as are the companions accompanying the doublet, but the main line is not itself double.

If we compare the groups at 5,461, 5,526, and 5,658 in spectrum *G* we cannot but help being struck by the marked similarity between them and by the similarity between the arrangement of the lines in the groups and the arrangement of the iodine absorption lines which occupy the region covered by the green mercury

line (spectrum *O*). The resonance groups are however on a vastly larger scale than the iodine absorption lines, the amplification being about thirty-fold. This is most strikingly brought out in spectra *K* and *L* which represent enlargements of the groups at 5,526 and 5,658 respectively. The width of the 5,461 mercury line within which all of the absorption lines which respond to the excitation fall is shown on the same scale at *M*. Speaking figuratively we may say that the iodine vapor acts something like a spectroscope of high resolving power, an extremely narrow group of absorption lines giving rise to similar groups on a much larger scale disposed at regular intervals along the spectrum.

We are now confronted with a great difficulty, for the groups are by no means strictly identical with each other or with the group of absorption lines, and we must ascertain if possible which lines in the resonance groups are associated with, or excited by, the lines in the absorption group.

I have made a beginning towards the solution of this problem by removing certain frequencies from the green mercury line by passing the light from the arc through bromine vapor before it entered the iodine tube. Some of the bromine lines coincide almost exactly with the iodine lines and these therefore cannot respond to the excitation since the necessary frequencies have been removed by the bromine filter. To apply a selective ray-filter within the region of the spectrum occupied by a single emission line seemed at first a rather large undertaking but the plan was found perfectly feasible, and very satisfactory photographs were obtained. The circumstance that the satellite lines (if one may so term them) which accompany the resonance doublets are somewhat differently disposed according as we use the green line of the Cooper-Hewitt lamp or the quartz lamp, furnishes us with another method of analysis. Up to the present time I have photographed only the satellite lines grouped around four of the resonance lines, and the circumstance that the general appearance of the groups of lines reminds one of a highly magnified image

of the group of absorption lines falling within the green mercury line, made me think at first that each line in a resonance group resulted from the stimulation of a definite absorption line. I no longer believe that this is the case, however, and until a further study of the subject is made it will be difficult to say just how the groups arise.

A study of the green mercury line in comparison with the absorption spectrum of iodine in the same region, with the mercury lamp running at different temperatures throws some light on the subject, however, and has most clearly indicated the lines along which the work must be carried in the future.

We are dealing with a group of seven iodine absorption lines, which for convenience we may designate as two doublets and a triplet, and number 1, 2, 3, 4, 5, 6 and 7, beginning at the short wave-length end (first doublet). If the mercury arc is running at a low temperature, as is the case in the Cooper-Hewitt lamp, the bright central component of the green line almost exactly bisects the second doublet (lines 3 and 4). It is obvious that, under these circumstances, one of the absorption lines is excited by a frequency slightly greater than its own, and the other by a frequency slightly less. The light which is reëmitted without change of wave-length (resonance radiation) gives us a single line so far as I have been able to find with the comparatively low dispersion brought to bear upon the resonance spectra. The 40-foot spectrograph would probably show it double, of course. The lines of the resonance spectrum however are double, and the components of each doublet are separated by a distance about 30 times as great as the distance between the absorption lines. This magnification of the doublet occurs only in the case of the light which is emitted with altered wave-length, and not at the primary line. As a working hypothesis we may ascribe it to excitation by a frequency intermediate between the frequencies of the absorption lines, and we may test our hypothesis by slightly altering the frequency of the exciting line, so as to make it approach one or the other of the two absorption lines. It

seems by no means impossible to accomplish this, since the distance between the absorption lines is only 1/120 of the distance between the D lines of sodium, and a very slight alteration in the pressure of the mercury vapor would give the required shift of the emission line. If the iodine vapor is excited by the quartz lamp we still get sharply defined lines in the resonance spectrum, notwithstanding the circumstance that in this case the green mercury line has broadened out into a continuous band of light which completely covers the group of absorption lines with the exception of the point midway between lines 3 and 4, where the green line is weakened by reversal.

This makes it seem doubtful if the hypothesis just suggested is correct. It will be necessary to excite the iodine vapor with the mercury lamp running under several different conditions as to current and temperature before any very definite statement can be made. That this method of investigation is sure to be a very fruitful one is made clear by spectrum *N*, Plate 2, on which I have shown the appearance of the green mercury line with the lamp at different temperatures, and the iodine absorption lines in coincidence with it. This is a drawing. Spectrum *O*, Plate 2, is a photograph of the green emission line of the quartz arc, when first ignited, taken in coincidence with the same line from the lamp at high temperature, the light being passed through iodine vapor. It will be seen that under this condition practically all of the light of the line is located in the middle component, which bisects absorption lines 3 and 4. It will be noticed, however, that the center of gravity of the line lies a little nearer line 3, whereas in the case of the Cooper-Hewitt lamp, which operates at a low temperature with about 3 amperes, the green line exactly bisects the absorption lines, as is shown by the photograph *S*, Plate 3 (upper spectrum the green line, lower spectrum iodine absorption). The green line of the Cooper-Hewitt arc seen "end-on" is shown by spectrum *P*, Plate 3, together with the iodine absorption lines. In this case the companion lines are enormously intensified in comparison to the middle bright

component which is weakened by self-absorption. The quartz arc, when first started, takes about 8 amperes, and the vapor is undoubtedly denser than in the Cooper-Hewitt lamp. This causes a slight apparent shift of the center of gravity of the line towards the region of shorter wave-length due to the brightening of faint components which lie close to the main line on this side. The green line of the quartz lamp at low temperature is shown in coincidence with the same line at high temperature by spectrum *Q*, Plate 3, and the high temperature line in coincidence with the iodine absorption lines by spectrum *T*. Spectrum *U* shows the line at medium temperature together with the absorption lines. These photographs were all made with the 40-foot spectrograph in the fourth order. Going back now to diagram *N*, Plate 2, we see that the exciting line may be made to assume a variety of intensity distributions according to the temperature and current consumption of the lamp. At medium temperature we find two dark lines within the broadened emission line (next to last diagram, *N*). The left-hand one of these I find results from reversal of the central component, and it persists as the temperature rises, as shown by the lower diagram. The right-hand one is the dark gap between the main line and the first component to the right, and this one gradually fades out as the temperature rises.

It is evident that much will be learned when photographs of the resonance spectra are secured with the iodine vapor excited by the line under all of these different conditions. At present we have at our disposal only the resonance spectra excited by the Cooper-Hewitt lamp, and the quartz lamp at high temperature. The change in the appearance of the four groups of resonance lines is shown in Fig. 1, which was drawn from the original negatives used for the preparation of spectra *F* and *G*, Plate 2. The most conspicuous feature brought out is that the strong doublets are shifted towards the violet in the case of the excitation by the high temperature arc. It is not an actual shift, but merely a change in the distribution of intensity among

the lines forming the groups. In addition to this, certain lines appear in one case which are absent in the other. This is especially noticeable in the group at 5,725 in which the second lines from the left are clearly displaced with reference to each other. I am of the opinion that the shift in the region of maximum intensity towards the violet in each group results from the

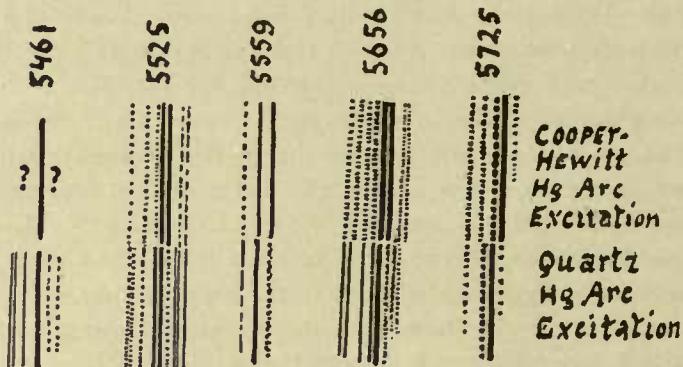


FIG. 1.

widening of the green line in the same direction, but it seems impossible to assign the lines in the groups to definite absorption lines until photographs have been secured with the exciting line under a larger number of different conditions.* Very probably the excitation of a single absorption line gives rise to resonance lines accompanied by fainter companions. The primary line at 5,461 is accompanied by these companions but is itself single, as I have already pointed out. In addition to varying the temperature of the lamp we may pass its light through bromine or some other vapor showing fine lines in its absorption spectrum, and so modify the appearance of the emission lines. This has already been accomplished. The light from the quartz arc rendered convergent by a large condenser was passed through a large spherical flask containing a small amount of bromine

* *Note added November, 1912.*—This has since been accomplished with very interesting results. The distribution of intensity among the lines forming the groups depends upon the strength of the current in the quartz arc.

in vacuo, the light subsequently coming to a focus in the iodine tube. (The air was exhausted by freezing the bromine to the wall with solid CO_2 and ether, and exhausting rapidly with a Gaede pump.) The effect of the bromine filtration of the exciting light was to remove the right-hand component of the triplet which lies to the left of the strong doublets at 5,525 and 5,660 in the resonance spectrum. See small inserts below *G*.

This same triplet is found to the left of the primary line in the resonance spectrum (5,461) at the bromine filtration weakened the right-hand member in this case also.

I have photographed the bromine absorption spectrum in coincidence with that of iodine with the 40-foot spectrograph. The two are shown by spectrum *V*, Plate 3, taken with sunlight, and by spectrum *R*, taken with the green line of the quartz arc. It seems probable that the line removed from each resonance group by the bromine filtration of the exciting light results from one of the absorption lines 2, 6 or 7, since these three are in coincidence with bromine absorption lines. We find however that the two outer components of the triplet appear in the resonance groups excited by the Cooper-Hewitt lamp, which has practically no energy at the point occupied by the iodine absorption line 2 while line 7 of the iodine absorption is in coincidence with the right-hand component of the mercury line (see *P*, Plate 3). I imagine therefore that this line is responsible for the right-hand member of the triplet removed by preliminary filtration of the green line through bromine. Further experimentation will of course be necessary before we can be at all sure of this point and I have attempted an analysis merely to indicate the line along which work is possible. The effect of the bromine filter is shown by the small photographs of groups 5,525 and 5,660 attached to the lower side of spectrum *G*.

A study of the satellite lines accompanying the resonance lines excited by the two yellow mercury lines has not yet been made. As has been pointed out, however, the character of the resonance lines is quite different according as we use the Cooper-Hewitt

lamp, or the high temperature one of quartz: It will be necessary to photograph the resonance spectra with the grating, passing the exciting light through the eosine screen to remove the green line, since the lines of the series excited by the 5,790 yellow line very nearly coincide with the lines excited by the green line. I have already photographed the absorption of the iodine vapor with the 40-foot spectrograph, using the light of the quartz mercury arc for the purpose. In coincidence with this spectrum I have photographed the emission spectrum of the Cooper-Hewitt lamp and also the absorption spectrum of sodium, to see whether the use of sodium vapor as a ray filter is practicable. On Plate 3, spectrum *X*, will be found the absorption spectrum of sodium and iodine within the 5,769 mercury line (quartz arc), the iodine spectrum being in the middle. Fourteen absorption lines of sodium are seen within the broadened yellow mercury line, and it is clear that the use of this vapor as a ray filter is certain to exercise a profound effect upon the resonance spectra. Spectrum *Y* on the same plate is 5,790 mercury line, two strong and three weaker lines, with a close pair a little further along towards the short wave-length region. It is probable that this pair have been responsible for some of the discrepancies in the observations made of this line with echelons and interference plates. Further reference will be made of this matter in the paper on "the satellites of the mercury lines," No. 10. The iodine absorption at this point of the spectrum is more complicated than at the other yellow line, and the photograph is unsuitable for reproduction, though sufficiently good for purposes of measurement. Spectrum *Z* shows the iodine absorption within the 5,769 mercury line (quartz arc) in coincidence with the emission lines of the Cooper-Hewitt lamp. The strong core of the line is in exact coincidence with an iodine absorption line, and the resonance lines excited by this line consist of sharp doublets. If the iodine line is a doublet, as is the case at the green mercury line, a resolving power of 300,000 does not show it. This point is of importance in connection with an hypothesis which I made as to

the origin of doublets in resonance spectra. The resonance doublets will be found on spectrum *B*, Plate 1. It seems highly probable that further investigations along these lines will do much towards clearing up many of the important points brought up in the present paper. The ease with which the iodine resonance can be studied makes me hope that the work will be taken up in other laboratories.

Note added Dec. 7, 1912.—I am at the present time securing satisfactory photographs of the resonance spectra with a resolving power capable of showing the components of the green mercury line; in other words, in the fourth order spectrum of the large plane grating used in the East Hampton spectrograph. This tremendous advance has been made possible by improving the method of illuminating the vapor. The wave-lengths of the resonance lines can now be determined to within 0.01 of an Ångström unit.

NO. 3.

SELECTIVE REFLEXION, SCATTERING AND ABSORPTION BY RESONATING GAS MOLECULES.

(PLATES 5 AND 6.)

In the present paper I shall deal with phenomena which, up to the present time, have never been made the subject of experimental investigation; and though elaborate mathematical treatments have been given by Planck, Lord, Rayleigh, Schuster, Lamb and others, no experimental data have ever been obtained. Through the discovery that the vapor of mercury, at room temperature, emits a brilliant resonance radiation when stimulated by monochromatic ultra-violet light of wave-length corresponding exactly to that of its so-called absorption line ($\lambda = 2536$), I have been enabled at last to obtain quantitative data on the subject.

It has been found that when the vapor is in a high vacuum there is no true absorption, the energy diverted from the primary beam of light being wholly scattered, as imagined by Planck in his treatment of the theory of absorption. The presence of a small quantity of air or other gas has been found to introduce the factor of true absorption, or the conversion of the energy of the light-waves into heat, and the ratio of the amount of energy scattered to that absorbed as a function of the pressure of the gas with which the mercury vapor is mixed has been determined. A very remarkable secondary resonance radiation of the gas not directly illuminated by the primary beam, but stimulated by the light which comes from the directly excited molecules, has been discovered, the study of which has enabled me to draw the conclusion that there is no true absorption except when the pressure is raised by the presence of air.

I have also succeeded in passing by gradual stages from the condition in which the resonance radiation is diffusely scattered to that in which, owing to the proximity of the molecules, it is regularly reflected from the surface of the gas mass. A resonance lamp has been constructed which emits light probably more homogeneous than that obtained from any source hitherto known, by the light of which I have succeeded in photographing the vapor rising from a drop of warm mercury into the air of the room like black smoke. So sensitive is the light of this lamp to the presence of mercury vapor, that I have been obliged to ventilate my room before each experiment, owing to the presence of mercury in the cracks on the floor, for the light of the lamp is reduced to one-half of its intensity by traversing a layer of mercury vapor at room temperature only 5 mm. in thickness.

The following topics will be discussed:

Introduction.

Resonance radiation of mercury vapor at room temperature.

Energy diverted from the primary beam.

Primary and secondary resonance radiation.

Destruction of the secondary radiation by molecular collisions.

Probability that the molecules continue to emit light after they leave the region traversed by the primary beam.

Ratio between scattered and absorbed light as a function of the pressure of the gas.

Transition from diffuse scattering to regular reflexion.

Absence of all traces of polarization.

Experiments with the resonance lamp.

INTRODUCTION.

The scattering of light by gas molecules has been the subject of mathematical treatments, but practically no experimental work has been done upon the subject, and we have no data whatever regarding the actual amount of energy diverted from

the primary beam by a molecule in exact resonance with the light-waves which excite it.

Lord Rayleigh has interested himself chiefly with the scattering which may occur when the molecules are not in resonance, as is the case in the scattering of the blue light by the molecules of the atmosphere. This case has been experimentally investigated by Abbott, who has measured the atmospheric absorption from the summit of Mount Wilson. Of greater interest, however, is the scattering by molecules resonating under the influence of the light-waves. But few cases of this are known, though this action has been made the basis of the theory of absorption developed by Planck. Some years ago I found that the non-luminous vapor of sodium at a comparatively low temperature, when illuminated by the light from a powerful sodium flame, re-emitted light of the same wave-length in all directions. This re-emission of light, without change of wave-length, by molecules of an absorbing gas, I named resonance radiation, to distinguish it from fluorescence, where there is in general an increase in the wave-length. Sodium vapor is, however, almost impossible to handle in a satisfactory manner, and is in consequence unsuitable for a quantitative investigation of the subject.

About two years ago I discovered that mercury vapor acts in the same manner, except that the phenomenon occurs in the ultra-violet region at the absorption line 2536. I first observed the resonance radiation of this vapor at room temperature in an exhausted silica bulb, the pressure of the mercury vapor being 0.001 mm.

This vapor appeared to be the ideal medium for a careful study of the subject in all of its aspects, except for the fact that everything has to be done by photography. The work has turned out even better than I had hoped, and I have been able to pass gradually from the case where the scattered light is radiated in all directions by the highly rarefied gas to that in which it is regularly reflected from the surface of the gas under high pressure.

I have already described the selective reflexion of mono-

chromatic light by mercury vapor,¹ in a paper which I shall have occasion to refer to later on.

Although I first observed the resonance radiation of mercury vapor nearly two years ago, I published nothing on the subject, as no quantitative data had been obtained. The observation was made in the following way. A small drop of mercury was introduced into a tube of fused quartz, closed by end plates of the same substance which had been ground flat and polished. These plates were fused to the ends of the tube, which had been flared out in order to prevent spoiling the figure of the central portion of the plates by fusion. The tube is shown in Fig. 1,

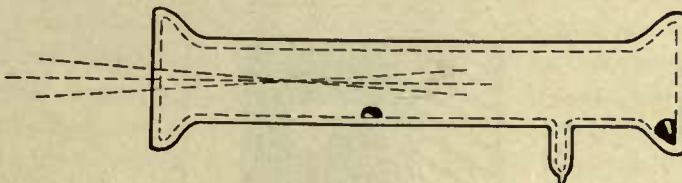


FIG. 1.

and was designed for a study of the dispersion of the vapor by an interferometer method, an investigation of which has been completed and will be described in a following paper. It was made by Heraeus and turned out quite as well as I had hoped, for I have had no difficulty in forming interference fringes with one beam of light traversing the tube, showing that the process of fusing on the end plates did not damage their optical quality. The tube was highly exhausted and sealed, and the light of a quartz mercury arc focused along the axis of the tube. The tube was now photographed from the side with a camera furnished with a lens of quartz, which was constructed in a few minutes from an old box used for storing photographic negatives. A quartz lens of about 18 cm. focus was fitted into a hole made in the bottom of the box, which was used standing on its side. A strip of thick sheet brass was cut to the same width as the plates

¹ Phil. Mag., vol. xviii., p. 187, 1909.

for which the box was made. To this strip was soldered another strip in which a circular aperture 8 cm. in diameter had been cut. This strip stood vertically in the box, and was provided with two spring clips, or supporting clamps, to hold the plate in place against the circular aperture. The camera was focused by sliding the strip along in the grooves which supported it. (These grooves were made originally for holding the plates.) The correct focus for the invisible rays with which we are concerned in the present paper was found by pointing the camera at the slit which had been mounted in the focal plane of the quartz spectrograph (to convert it into a monochromator), and ob-

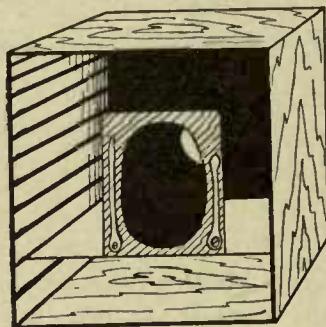


FIG. 1 a.

serving the focus with a piece of uranium glass. The distance from the lens to the slit from which the ultra-violet rays diverged was then measured. This gives the correct distance at which the object to be photographed must be placed in order to be properly focused. The camera is shown in Fig. 1 a. I have found that much time is saved by the use of a camera of this description, for the plates can be cut carelessly and in a hurry, as they do not have to be of an exact size, and no time is lost in loading or unloading a plate-holder. In ultra-violet work of this description, where the sources of error and all other unexpected troubles and difficulties have to be located by photography, the time saved in this way amounts to a good deal. In

the present work I have taken about six hundred photographs, and have saved the many hours that would have been spent in fussing with plate-holders and misfit plates. The hinged back of the box can be swung aside and the plate inserted in the supporting clamps in a few seconds, the room being darkened of course.

The Westinghouse quartz arc was enclosed in a box and the collimator of the quartz spectrograph introduced through a small hole. In this way diffused light, which would have spoiled everything, was shut out. The lamp was started by pulling a string which passed through a small hole in the top of the box, and extinguished at the right moment by opening a switch.

The monochromatic light from the slit of the quartz spectrograph was either made parallel, or brought to a focus by means of a pair of quartz lenses of 30 cm. focus each, the condition of the pencil of rays being tested with the uranium glass plate.

The photograph taken two years ago with the Heraeus lamp of the tube closed with flat quartz plates showed an image of the cone of rays traversing the high vacuum precisely as if the tube were filled with dense smoke. The tube was at room temperature, and the density of the mercury vapor was about 0.001 mm., nevertheless an exposure of fifteen or twenty seconds was all that was necessary.

Owing to my absence from Baltimore I was unable to take up the work again until this winter. In the meantime I had secured a Westinghouse Cooper-Hewitt quartz mercury arc which was very much more powerful than my old Heraeus lamp. These quartz arcs emit the strong line of wave-length 2536, and it is this light alone which excites the resonance radiation.

To my surprise, on repeating the experiment of two years ago with the new arc lamp, I found no trace whatever of the luminous cone of light, even with an exposure of several minutes. On looking up my notes, however, I found that in the earlier experiments I excited the lamp with a high potential current from a transformer, running it at a comparatively low temperature.

It immediately occurred to me that in the present case I was working with the lamp at high temperature, and that the 2536 line was very likely reversed, the wave-length necessary for the excitation of the resonance radiation being removed by absorption. I accordingly allowed the lamp to become quite cold, and made my exposure when the lamp was first lighted, when its light is quite violet in color. On developing the plate I found that a five seconds exposure gave me a more intense cone of light than anything that I had ever observed before. It was absolutely black on the negative. Moreover, the vapor outside of the cone of focused rays appeared to be glowing at the end of the tube where the beam passed in. As the fused quartz is somewhat fluorescent under the action of the rays emitted by the lamp, it was necessary to prove that this light did not come from the walls of the tube. That such is not the case I shall show when we come to subsequent experiments.

A photograph of the resonance radiation in the tube is reproduced on Pl. 5, Fig. 1.

It was next necessary to observe the spectrum of the light emitted by the mercury vapor, and the slit of a quartz spectrograph was opened wide and brought up close to the silica tube. Two photographs were made—the first of ten seconds exposure immediately on starting the Westinghouse lamp; the second, also of ten seconds after the lamp has been running half a minute. These photographs are shown in Pl. 5, Fig. 2. In the second spectrum the broadened image of the slit is shown at the 2536 line, the other lines appearing narrow. These lines result from the circumstance that some direct light from the arc illuminated one of the jaws of the slit. The upper spectrum, taken after the lamp has been in action for half a minute, is identical with the second, except that the broad image of the slit is absent, showing that the resonance radiation has disappeared. I then made a series of four spectra taken one after the other. These showed that the resonance radiation was very strong during the first five seconds of the lamp's operation, quite faint during

the second five seconds operation, the merest trace during the third five seconds, and completely gone in the next five seconds. In all of the subsequent work I accordingly allowed the lamp to become quite cold, and extinguished it after a run of exactly five seconds. This insured uniformity in the exposures. The slit of the spectrograph was now made as narrow as possible and five exposures were superposed of five seconds each, the direct light from the arc being screened from the slit. The spectrum showed only the 2536 line, exceedingly narrow and sharp, thus proving that we are dealing with a very beautiful case of pure resonance radiation. In fact, I suspect that this radiation will be found to be the most homogeneous which we have, for the vapor is not only at a lower pressure than is usual in vacuum-tubes, but *it is at room temperature*. On Pl. 5, Fig. 2, the third spectrum is that of the resonating vapor, the fourth spectrum that of the mercury arc.

I next investigated the effect of raising the temperature of the tube which was mounted in a small air-bath. It was found, as was to be expected, that, as the temperature rose, the cone of emitted light became shorter and brighter, until it finally disappeared, the emitted light coming from the inner surface of the plate where the incident beam of light entered. As no especial significance is attached to the records obtained in this way, I shall postpone any further discussion of the effects of increasing the density of the vapor until I take up the subject of the transition from diffuse scattering of the emitted light to its recombination into a regularly reflected wave, which can be accomplished by increasing sufficiently the density of the vapor.

We will now take up the important subject of the amount of energy diverted from the incident beam by the resonating gas molecules.

AMOUNT OF ENERGY DIVERTED FROM THE PRIMARY BEAM.

It is clear at the outset that if we wish to determine the amount of energy diverted by the resonators when they are in exact

synchronism with the light-waves, it is useless to make observations upon the intensity of the light after it has suffered transmission through the vapor, even if we are dealing with what we are accustomed to call monochromatic light. All spectrum lines have a finite width, and the particular frequency scattered by the resonating molecules may constitute but a small fraction of the total energy of the spectrum line used to excite the vapor; in other words, it is only the centre of the line that is effective in exciting resonance, the edges of the line not being reduced in intensity by the transmission through the gas. What we wish to determine is the reduction in intensity of that portion of the line, or in other words the frequency, which is capable of exciting the natural period of vibration of the molecule. It appeared to me that the most direct way of investigating this question was to take the intensity of the cone of light as the measure of the intensity of the primary beam, for there appears to be no doubt but that the intensity of the resonance radiation is proportional to the intensity of that particular frequency in the exciting light which is capable of setting up resonance. I accordingly made a very large number of photographs with different times of exposure and different vapor densities, and measured the photographic density of the image at different distances from the point where the light entered the vapor. This gives us a measure of the rate at which the vapor cuts down the amplitude of the exciting frequency as the wave moves through the medium. The method by which these measurements were made will be described presently, and for the present I need only point out that the usual precautions necessary in photometric work by photography were taken. The mercury vapor in this case was not contained in the quartz tube, for it was impossible to get a good image of the excited region close up to the point at which the beam entered on account of the irregular refraction by the wall of the tube. A rectangular box of brass with windows of crystal quartz plates, which I shall describe presently, was used, and by paying attention to adjustments, it was possible to get

beautifully sharp images of the excited region close up to the surface of the window through which the light entered. I made measurements on fully a dozen plates taken on different days, and found that the intensity of the primary beam was reduced to one-half of its value after travelling for a distance of 5 mm. in mercury vapor at a pressure of 0.001 mm. The smallest value found was 4 mm. and the largest 6 mm. for a reduction to half intensity, a variation due without doubt to the circumstance that the room temperature varied by several degrees from day to day. This variation in the temperature of the room was just about sufficient to account for the slight differences observed, and we can safely assign the value of 5 mm. for a temperature of 22° C. Measuring the intensity along the path of the beam it was found that the ordinary law of absorption was very closely followed, *i. e.*, a 10 mm. layer reduced the intensity to one fourth and a 15 mm. one reduced it to one eighth of its original value. It appeared to me, however, that the reduction of the intensity did not follow this law exactly, but that the intensity was a trifle greater after 15 mm. had been traversed than the intensity calculated on the assumption that every 5 mm. effected a reduction of one half. This is in agreement with a calculation made by Schuster in his paper on "Radiation through a Foggy Atmosphere,"² though the differences in this case are not much larger than the probable errors in the measurements. The beam of light which entered the cell was made accurately parallel by means of a quartz lens and passed through a square aperture (measuring 5 mm. on a side) perforated in a black card. In this way a beam of uniform cross-section was obtained, which was of course necessary if the measurements were to be of any value. Only the ultra-violet 2536 light entered the cell, a quartz spectrograph being used as a monochromator.

We are now in a position to consider the amount of energy diverted from the primary beam by each molecule.

Lamb, in his theoretical treatment of the absorption of light

² *Astrophysical Journ.*, vol. xxi, p. 6, 1905.

by a gas, published in the Stokes Commemoration of the Camb. Phil. Soc., sums up a calculation in the following words: "Hence in the case of exact synchronism, each molecule of gas would, if it acted independently, divert per unit of time nearly half as much energy as in the primary waves crosses ⁱⁿ a square whose side is equal to the wave-length." This means, if I am not mistaken, that if we had a density such that there was one molecule in each cube the sides of which were equal to the wave-length, the intensity of the light would be reduced by one half by traversing a single layer of molecules, while a density ten or twenty times as great as this ought to give selective reflexion, since the wave would be practically stopped before penetrating to a depth of more than a small fraction of a wave-length.

Let us now compare this calculation with the values which have been determined. At a pressure of 0.001 mm., which is about the pressure used, the average molecular distance is such that we shall have on the average one molecule of mercury in every cube the sides of which are only very little larger than the wave-length (or more exactly 0.0003 mm.), which quantity divided into 5 mms., the distance traversed for a reduction of intensity equal to one half, gives us 16,000, that is to say 16,000 molecules must be passed before one half of the energy is removed from a square element on the wave-front measuring λ on each side.

Of course this calculation is made on the assumption that all of the molecules are equally effective in scattering the light. It is however possible, even probable, that but a small percentage are, at any given moment, in the condition to act as resonators. Experiments on the dispersion and magnetic rotation of metallic vapors and luminescent hydrogen give evidence that but a small percentage of the molecules are at any instant concerned in the production of the phenomena in question.

PRIMARY AND SECONDARY RESONANCE RADIATION.

Photographs of the luminous cone of mercury vapor at room temperature contained in the quartz tube appeared to prove that the vapor outside of the cone of vapor directly excited by the primary beam was itself luminous. It was observed, however, that the fused quartz phosphoresces with a violet light under the influence of the ultra-violet light, and I did not feel perfectly sure that the light did not come from the wall of the tube. To eliminate such a possibility a hollow box of brass was constructed (see Fig. 2), two adjacent sides of which were left open, and closed with thin plates of quartz (crystal) which is not phosphorescent. The inside of the box was heavily smoked, and the

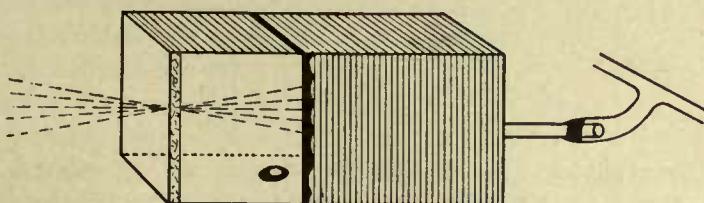


FIG. 2.

plates cemented in place with sealing-wax. A drop of mercury was introduced and the interior of the box put in communication with a Gaede pump and exhausted. The ultra-violet light was focused at the center of the box, entering through one of the quartz plates, and the resonance radiation photographed from the side through the other plate. It was found that, unless the pressure of the air was less than three or four millimetres, no trace of any secondary radiation was present. On lowering the pressure of the residual air it developed rapidly, however, and after the pump had been in operation for several minutes, the luminous glow filled the entire interior of the box, the luminous cone being nearly lost on the strongly luminous background. With correctly timed exposures the directly excited resonance radiation is always four or five times brighter than the secondary

radiation. Over exposure may, however, increase the effect of the secondary until it equals that of the primary, causing the outlines of the primary beam to disappear almost completely, as in the first picture in Fig. 4, Pl. 5.

The intensity of the secondary radiation depends upon the cross-section of the primary beam, as does also the rate at which its intensity diminishes with increasing distance from the primary rays. With an exciting beam of square cross-section (5 mm.²) the intensity of the secondary radiation half a millimetre from the edge of the beam was found to be nearly one third of the intensity of the adjacent primary radiation. Its intensity fell off with increasing distance as follows:

Distance.	Ratio.
0.5 mm.	1/3
1.5 "	1/6
2.5 "	1/10
3.5 "	1/30

Four photographs of the phenomenon are reproduced on Pl. 5, Fig. 4. A vacuum-tube was put in circuit with the tube leading to the pump, to serve as an auxiliary manometer, and it was found that the secondary radiation did not appear at its maximum intensity until the green fluorescence due to cathode rays appeared in the vacuum-tube.

It is clear from the photographs that when the mercury vapor is in the highest possible vacuum, the light which it emits is capable of exciting a secondary radiation in the surrounding vapor which lies wholly outside of the path of the primary exciting beam. The presence of air at 4 or 5 mm. pressure, while it materially decreases the intensity of the primary resonance radiation, causes the secondary radiation to disappear entirely. In the four photographs which are reproduced I have recorded the pressure of the residual air in each case. To make sure that the disappearance of the secondary radiation was not due to a weakening of the primary radiation, I gave an exposure of four times the normal one, with air at 4 mm., and though the cone was very

much blacker on the plate than on any of the others, there was no trace of any luminosity in the surrounding vapor.

This action of a small trace of air is most remarkable, and it is of the utmost importance to determine the explanation. Although the vapor which is in the path of the primary beam glows with almost undiminished brilliancy, the light which it gives out seems powerless to excite the surrounding vapor to luminosity. It seemed possible that the damping due to molecular collisions rendered the emitted light less homogeneous and therefore incapable of exciting the vapor, in spite of the fact that the absorption band must be regarded as broadened to a similar amount. This point is one which requires very careful investigation, and if the cause can be found much light may be thrown upon the nature of the effects of molecular collisions upon radiation. An interferometer study of the light of the resonance radiation of mercury vapor in *vacuo* and in air at low pressures will probably clear up the matter. It occurred to me that it might be possible that the emission of light by the vapor surrounding the primary cone might not be due to light emitted by the vapor directly excited, but to the circumstance that, owing to the great length of the mean free path, the mercury molecules continued to emit light after flying outside of the limits of the primary beam. The action of a small amount of air in destroying the luminosity would follow at once as a result of the reduction in the length of the free path, the luminosity being destroyed by the collisions.

PROBABILITY THAT THE MOLECULES CONTINUE TO EMIT LIGHT
AFTER THEY LEAVE THE REGION TRAVERSED
BY THE PRIMARY BEAM.

Fortunately this is an hypothesis which is very easily tested by experiment, for we have only to divide the cell into two compartments by means of a partition of quartz, passing the exciting beam immediately below and close to the under side of the horizontal partition. The partition will stop the moving molecules, but will transmit the light emitted by the vapor

illuminated by the primary beam. A small plate of quartz 1.5 mm. in thickness was cemented to the front window of the cell as shown in Fig. 3, and the cell exhausted until nothing but the green phosphorescence was visible in the discharge-tube. The resulting photograph showed that there was considerable luminosity in the upper chamber, but it appeared to be of somewhat less intensity than that of the vapor in the lower chamber.

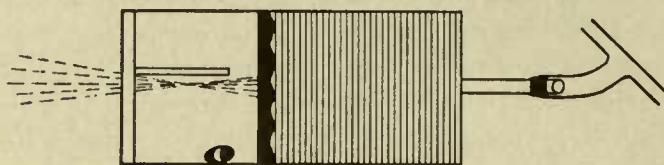


FIG. 3.

The photograph, however, was not very satisfactory owing to the thickness of the partition. The cell was accordingly made over again, with a partition consisting of a quartz plate only .25 mm. in thickness, and the same phenomenon was found, somewhat greater intensity of the secondary radiation in the compartment traversed by the exciting beam. Calculation of the reflecting power of the quartz plate from its refractive index for the wavelength in question showed that a reduction of intensity of 10 per cent. was to be expected from this circumstance, but this did not seem to be sufficient to explain the observed diminution of the intensity; and careful measurements of the intensity of the secondary radiation at equal distances from the centre of the primary beam were made by comparison with a plate exposed in strips by gradually increasing amounts of time, which was developed with a photograph of the cell for exactly the same length of time. These measurements showed that the effect of the thin partition was to reduce the intensity of the secondary radiation by an amount varying from 25 to 30 per cent. This appears to be very strong evidence of the persistence of the luminosity of the molecule after it leaves the region traversed by the exciting beam. Direct evidence of the phenomenon is much

to be desired, but I have been unable to think of any method, for we cannot make a screen which will transmit the moving molecules but cut off the light.

It is evident, however, that the primary cause of the destruction of the intensity of the secondary radiation by the presence of air at three or four millimeters pressure is to be sought elsewhere, as fully 75 per cent. of the secondary radiation results from the light of the primary. I shall now show that the effect of the air in reducing the intensity of the secondary radiation results from the introduction of the factor of true absorption as contrasted with molecular scattering.

MOLECULAR SCATTERING AND TRUE ABSORPTION.
RATIO OF THE TWO QUANTITIES.

It is easy to see that, if true absorption occurs as well as scattering, the intensity of the secondary radiation will be greatly diminished in intensity. When the vapor is in a vacuum of less than .01 mm. it is probable that the energy diverted from the primary exciting beam is all scattered, and no true absorption occurs. We should of course find what appeared to be an absorption line in the spectrum of the transmitted light, and yet the molecules would not be absorbing energy but merely diverting it from the primary beam and sending it out in all directions. The molecules lying in the path of the beam will glow with a certain intensity, while those which lie outside of the path of the beam will be illuminated by the radiating molecules which are directly excited, and will in consequence emit a light of a lesser intensity. Suppose now that by the introduction of air at a pressure of 5 mm. the intensity of the light emitted by the directly excited molecules is reduced to one third of its original value. By means of a threefold increase in the intensity of the exciting light we can raise this intensity to its original value, so that the same amount of light is available for the excitation of the secondary radiation as before. The intensity of the secondary radiation excited under these circumstances will, however,

be only one third of its former value, since two thirds of the energy received from the directly excited molecules is transformed into heat by the true absorption which has been introduced by the presence of the air. The intensity of the secondary resonance radiation in comparison with that of the primary will consequently be much less (one third) than when the mercury vapor was in a high vacuum. This hypothesis was tested by experiment and practically proven. In the first place a very careful series of measurements was made of the reduction in the intensity of the primary resonance radiation by the introduction of air. The pressure of the air was measured with a McLeod gauge, and the duration and intensities of the excitation were made as nearly equal as possible.

The exposures were all made on the same plate, which was pushed along in the supporting clamps, the mercury lamp being allowed to cool down completely between exposures. To insure against accidental errors, a large number of plates were exposed, and the measurements made from each were compared. One of these plates is reproduced on Pl. 5, Fig. 8. The air pressure in the cell is marked on each picture. The exciting beam enters the cell from the right, and two thirds of the quartz window was screened off, so that a number of exposures could be made on the same plate. In the first picture (pressure 0.01 mm.) the secondary radiation from the region not excited by the primary beam is very conspicuous, less so in the second and nearly gone in the third. The intensities of the primary radiation at the point where the incident beam entered the cell was measured by comparing the density of the negative with the density of a plate exposed in strips for times increasing gradually from 5 to 300, which plate was developed simultaneously with the other. The comparison was made in a very simple way which, with practice, was susceptible of considerable accuracy. A clean cut was made with a sharp knife through the film on each plate, perpendicular to the direction of the strips on the comparison plate, and through the region at which the density was to be

measured on the other plate. The film was removed along one side of the cut in each case, exposing the clear glass. The two plates were now placed in contact film to film, and the comparison strip slid along until a perfect density match was made with the photograph, the dividing line between the two disappearing. In practice it was found advantageous to cover the plates with a black card perforated with a small rectangular aperture, which was brought over the region under investigation, and the best match could be made by throwing the eye a trifle out of focus, thus causing the very narrow line separating the two halves of the field to disappear.

The values found are given in the following table.

Air Pressure in Mm.	Intensity of Primary Resonance Radiation.	Absorbed Energy.
.01	300	0
.45	230	70
1.10	200	100
2.20	170	130
6.20	100	200
9.50	70	230
14.20	50	250
18.00	40	260
32.00	12	288

If we plot these values, taking intensities as ordinates and air pressures as abscissæ, we obtain a curve practically identical with the curve obtained with iodine vapor, which shows that the effect of the air upon the intensity of the emitted radiation is about the same in the two cases. In the third column I have given the amounts of the energy absorbed in each case. These values are merely the differences between the amounts of the emitted energies and the energy emitted when the vapor is in a high vacuum (300), and are calculated on the assumption that the total energy diverted from the primary beam is the same in the two cases, *i. e.*, that the presence of the air does not influence the amount of energy removed from the beam by the resonating gas molecules.

That this is in reality the case was shown by the following experiment. A double cell, Fig. 4, was made by soldering a cross partition along a diameter of a short section of large brass tube, the ends of which were closed with quartz windows.

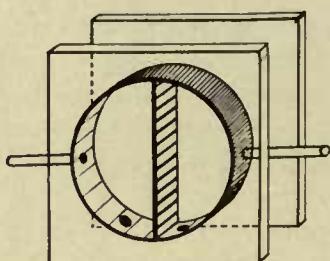


FIG. 4.

The length of the tube was 17 mm., and the diameter 30 mm., and two small brass tubes permitted either compartment to be exhausted to any desired pressure. In measuring the energy diverted from the primary beam by the vapor, we must be certain that we use light which is in exact synchronism with the resonating molecules. The light must be far more homogeneous

than the ray isolated by the quartz spectrograph from the light of the mercury arc. I used therefore what I shall hereafter refer to as the resonance lamp, a small quartz bulb, closed at the bottom with a flat plate of polished fused quartz, which was fused on in the same manner as the end plates of the long tube previously described. This bulb contained a drop of mercury, and was highly exhausted and sealed. The light from the quartz spectrograph was focused through the side of the bulb as close to the center of the flat bottom as possible. The adjustments were made by means of a small piece of uranium glass, which enables one to locate the path of the rays by its phosphorescence. It is most important to prevent the light which is reflected from the walls of the bulb from getting at the photographic plate. This gave a good deal of trouble, but by means of the device shown in Fig. 5, it was practically eliminated. A wooden box was made, measuring $40 \times 10 \times 10$ cm., and a large circular hole cut in one end which was covered with a cone of black cardboard made by cutting out a circular disk, cutting along a radius and pasting the cut edges together, overlapping them about 2 cm. A small round hole was burned through the apex

of the cone, and this was placed against the flat bottom of the resonance lamp. A quartz lens mounted in a partition of the box rendered parallel the rays which came from the resonance lamp through the small hole, so that the intensity of the light

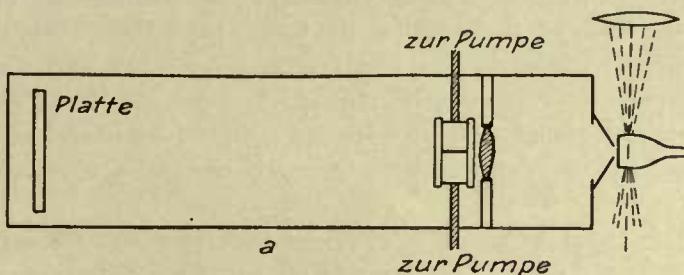


FIG. 5.

after its passage through the cell could be recorded close to the cell or at a distance from it. The importance of doing this is apparent from the following considerations. If we place a photographic plate close against the double cell containing the vapor, it will be illuminated by the primary beam which has traversed the cell and also by the scattered resonance radiation. If, however, we place the plate at a distance, say at the other end of the box, the primary rays, being parallel, will reach it with undiminished intensity, while the effect of the scattered radiation will be negligible, since its intensity diminishes according to the law of inverse squares. No difference should be found with the plate in the two positions for the light which has gone through the compartment containing air and mercury vapor, since, as we have seen, the presence of the air destroys the resonance radiation. The experiment was made in the following way. One compartment of the double cell was highly exhausted and the other to a pressure of 3 cm. A strip of photographic plate 1.5 cm. in width was mounted close to the cell and received the light which had traversed the lower half of each compartment. A larger plate was mounted at the other end of the box, and

received the light which passed above the first plate, and had traversed the upper halves of the compartments. Thus four records were obtained at once under precisely similar conditions as regards exposure-time and development. Much trouble was experienced in getting things adjusted so that the intensity close to the lens and at the end of the box came out the same with the cell removed, which is of course a necessary preliminary experiment. It was finally found that the air of the room contained enough mercury vapor to reduce the intensity of the light from the resonance lamp by nearly one half as it traversed the length of the box.

This is not so surprising when we remember that the earlier experiments showed that the primary beam was reduced to one half of its intensity (*i. e.*, the frequency capable of exciting resonance was) by traversing 5 mm. of the saturated vapor at room temperature. The trouble was overcome by opening the windows and thoroughly ventilating the room before each experiment. One is reminded of the trouble experienced in carrying on certain investigations in laboratories which have become infected by radium!

One of the photographs obtained with the double cell is reproduced on Pl. 5, Fig. 3. In this case one compartment (the upper) was free from mercury vapor, while the other contained it. This particular cell was, however, only 8 mm. in thickness, and gives a good idea of the powerful absorption of the highly homogeneous light from the resonance lamp by a shallow layer of the vapor at room temperature. The other photographs showed that the energy diverted from the primary beam was the same for mercury in a high vacuum and in air at 3 cm. pressure, so that the calculation of the absorption-scattering ratio which I gave provisionally was justified.

It was found, however, that if air at atmospheric pressure was admitted to one compartment the absorption was decreased by more than one half. This is just the opposite of what I found three years ago, when I discovered that I could photograph the

2536 absorption line by passing the light of a cadmium spark through a tube 3 meters long containing mercury vapor at room temperature, if the tube contained air at atmospheric pressure, while no trace of the line appeared if the tube was exhausted. There is, however, no real discrepancy, for the effect of the air, as I have shown previously, is to broaden the absorption line. This circumstance was discovered independently by Ångström in the case of CO_2 . The present experiments appear to show as well that, while the line is broadened, the intensity of the absorption at the center of the line is materially reduced. I have observed the same thing with iodine vapor, the lines becoming fuzzy and less black when air is admitted to the tube.

The failure to obtain the absorption line in the earlier experiment with the three-meter tube exhausted was of course simply due to the insufficient resolving power of the spectrograph employed.

In the experiments with the double cell which I have just described, I was unable to find any distinct evidence that the resonance radiation contributed to the darkening of the photographic plate, for there appeared to be no difference between the case of a plate placed close against the cell and one placed at a distance. There is reason to believe that the radiations emitted by a resonator lag in phase behind the phase of the primary wave by 180° , that is they should reduce the intensity of the primary wave by interference. This is a delicate matter to investigate experimentally, but I have made one or two attempts. If we place a black screen perforated with two small holes in front of the cell, we can limit the radiation which traverses the cell to two beams of small cross-section, each compartment transmitting one of them. The primary wave will now record itself on the plate as two small spots of the same diameter as that of the apertures. The short column of vapor traversed by the narrow beam in the high vacuum compartment gives off scattered resonance radiation, and we should expect this to record itself as a faint penumbra around the sharply defined image imprinted

by the primary beam. No trace of any such penumbra was found, from which we can infer that the effect is negligibly small in comparison with that of the primary wave. This made me suspect that, even when the vapor is in a high vacuum, some true absorption of energy must take place, for it is obvious that the magnitude of the effect due to the resonance radiation will decrease in proportion to that of the primary wave as the factor of true absorption is introduced. It appeared possible to determine in this way, just what proportion of the energy diverted from the primary beam was absorbed and what proportion was scattered. I accordingly placed the quartz lens at the centre of the box, with the plate and absorption cell at the end opposite to that on which the perforated paper cone was fastened. This gave me a sharply focused image of the circular aperture in the

cone on the photographic plate, which was placed as before with the film in contact with the anterior quartz window. I now got a very intense beam of light from the resonance lamp, and a very black spot upon the plate with a distinct trace of a corona around it due to the scattered radiation (Pl. 6, Fig. 13). Air was now admitted to the cell and the experiment repeated.

No trace of the corona appeared as was to be expected, as is shown in Pl. 6, Fig. 12.

This experiment will be better understood by reference to Fig. 6, in which the scattered rays which produce the corona are represented by arrows. The question now is, how great an effect from these scattered rays are we to expect in comparison with the effect produced by the primary beam after its passage through the cell? A rigorous calculation involves some difficulties, but we can make an approximate estimate in the following way. In the experiment as it was tried, the

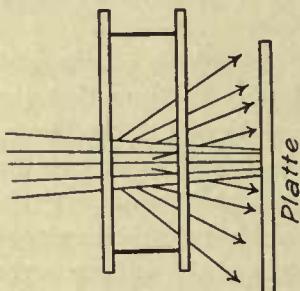


FIG. 6.

thickness of the cell was 10 mm., and the intensity of the primary beam was therefore reduced to one quarter of its original value, or in other words 75 per cent. of the energy was scattered, and 25 per cent. reached the plate as direct rays and recorded itself on a circular area 4 mm. in diameter. It is evident that the intensity of the scattered resonance radiation from the first layer of molecules encountered by the primary beam will be most intense, but its intensity will be reduced when it reaches the plate, by its passage through the gas, in the same proportion as is the intensity of the primary ray, which excites the last layer of molecules to a much feebler luminosity. The intensity of all of the layers as seen by the photographic plate would thus appear to be equal. It is now evident that the 75 per cent. of the energy diverted from the primary beam, since it is given out in all directions, is distributed over a complete sphere, and we shall probably go not very far wrong if we assume it all as coming from the first layer, which will make our sphere of radius equal to 10 mm. (the thickness of the cell), for in the actual experiment the photographic plate was placed in contact with the anterior window, and not at a distance as shown in the figure. The area of the sphere is 1256 mm. and the area illuminated by the primary beam 12 mm., the ratio of the areas being as 1 is to 105. We have then a radiation of intensity 3 (the 75 per cent. scattered referred to above) distributed over area 105, and radiation of intensity 1 concentrated on area 1. The direct image ought, therefore, to be about 35 times as bright as the corona. I made a rough measurement of this ratio and found it to be in the neighborhood of 1 : 40, which agrees as well as we could expect, considering the way in which the calculation was made. The calculation was made on the assumption that no true absorption occurred, and the fact that there is some agreement between the calculated and the observed ratio indicates that we are dealing with pure scattering when the mercury vapor is in a high vacuum. The destruction of the corona by the admission of air is the direct consequence of the introduction of the factor of true absorption. I am of the

opinion, however, that the ratio of the intensity of the secondary radiation to that of the primary, furnishes us with a better method of determining the ratio, and as I have already mentioned, the value obtained leads me to think that in a high vacuum there is no true absorption. A rigorous calculation of the ratio under specified conditions is much to be desired, and could be easily tested by experiment. The calculation could be made for a beam of either rectangular or circular cross-section. I believe that a beam with a square cross-section will prove best, and it must be remembered that in the experiment we photograph the entire mass of the gas, as seen from the side. I found that with a beam of this description the intensity of the secondary radiation close to the beam of primary radiation was in some cases equal to one quarter of the value of the latter, though it fell off very rapidly in value as the distance from the primary beam was increased.

POSSIBILITY OF CHANGE OF WAVE-LENGTH. METHOD OF THE DIFFERENTIAL VACUUM.

It thus appears that the destruction of the secondary resonance radiation is the result of the introduction of the factor of absorption, but it seemed best to test other hypotheses if possible. The only alternative that I have been able to think of is the possibility that the presence of the air alters the wave-length of the emitted light slightly so that it is no longer capable of exciting the vapor. The change necessary to accomplish this would be very slight, too small in all probability to be detected by any spectroscope except those of the highest resolving power. Another method, equally satisfactory and involving less difficulty than the use of a spectroscope, occurred to me. This we may call the method of the differential vacuum. A double cell with a quartz partition was constructed, of the form shown in Fig. 7. Each compartment contained a drop of mercury, and the monochromatic light from the arc was focused at the center of the lower compartment, which was exhausted to a pressure

of 6 min., previous experiments having shown that the secondary radiation is practically unnoticeable at this pressure. The upper compartment was highly exhausted. The point at which the rays were focused was brought as close as possible to the under side of the horizontal partition separating the two cells, and as

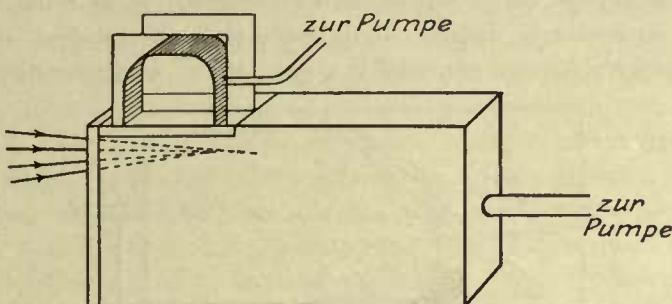


FIG. 7.

close as possible to the window through which the radiation was photographed, to avoid the loss of light due to an intervening layer of vapor. If now there is a change of wave-length due to the air in the lower compartment, the light (emitted by the directly excited vapor) which passes up through the quartz partition will be unable to stimulate the vapor in the upper compartment. If, on the contrary, the absorption hypothesis is correct, the vapor in the upper compartment will glow, since we have eliminated absorption here by the complete removal of the air. The photograph showed the secondary radiation in the upper compartment, and the ratio of its intensity to that of the primary was about the same as when both compartments were completely exhausted. This disposes of the second hypothesis, and is fully in accord with the absorption explanation.

TRANSITION FROM IRREGULAR SCATTERING TO REGULAR REFLECTION BY THE MOLECULAR RESONATORS.

I have already alluded to the selective reflection of monochromatic light by very dense mercury vapor, which I made a

study of some years ago, and the transition from diffuse scattering to this regular reflection has been made the subject of experimental investigation. Regular reflection can occur only when the resonators are so closely packed together that the primary wave is stopped completely by a layer the thickness of which is of the order of magnitude of the wave-length. If the resonators are so sparingly distributed in space that the incident wave penetrates to any appreciable depth, their radiations do not

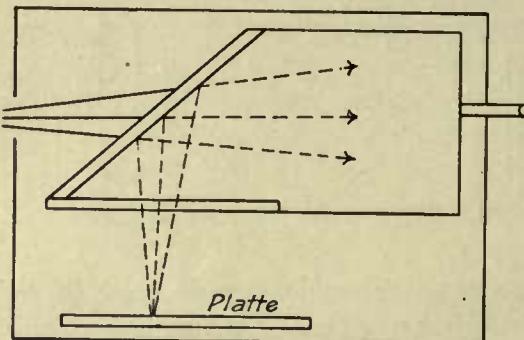


FIG. 8.

combine to form a reflected wave in the usual sense of the term. Planck, I think, has somewhere mentioned the circumstance that the radiations from the resonators destroy the primary wave by interference on account of their lag in phase, while those travelling in the opposite direction, there being no primary wave in this direction with which they can interfere, give rise to a wave which constitutes selective reflection. If this occurred, except in the special case in which the wave is stopped at the boundary, it would constitute what we might term "volume reflection" as contrasted to surface reflection, but the phenomenon has no existence, I feel sure. It seemed so easy, however, to get evidence of volume reflection if it existed, that I made one experiment, rather with the idea of convincing myself of its non-existence than anything else. A cell was made of the form shown in Fig. 8 and a divergent beam passed into it through the oblique quartz plate. If even

a very small percentage of the energy emitted by the resonators was returned towards the source, *i. e.*, in the direction of the primary rays reversed, we should have a converging system of rays which would be in part reflected from the oblique quartz plate and come to a focus on the photographic plate P. The plate, however, showed only a uniform darkening due to the light irregularly scattered by the resonators.

We do, however, obtain regular reflection when the density of the vapor is so great that the wave can penetrate only to a very small depth, and I next investigated the subject of the density at which the change from scattering to regular reflection takes place. A quartz bulb containing a drop of mercury, exhausted and sealed, was mounted just above a vertical chimney of sheet iron which served to immerse the bulb in the hot gases rising from a large Bunsen burner. A high temperature quartz thermometer was mounted with its bulb in contact with the quartz bulb, and by regulating the height of the flame of the burner, the bulb could be kept at any desired temperature. A divergent beam of the 2536 light was thrown upon the bulb by the quartz spectrograph, and the bulb photographed with the quartz camera. At room temperature the entire interior of the bulb was shown by the photograph to be filled with a uniform glow. As the temperature rose this glow was confined to the wall which received the direct rays from the spectrograph, owing to the failure of the radiation to penetrate to the interior. As the density of the vapor increased this glow appeared to draw in or close around the bright point which represented the image of the source reflected from the inner wall of the bulb. Two of these points usually appear in the picture, one reflected from the outer, the other from the inner wall. They are the virtual images of the source in the spherical mirror formed by the wall of the bulb. This contraction of the glow struck me as very peculiar, as it reminded one of the reflection from a slightly corrugated surface, or a surface which has been very finely ground but not polished. I obtained it with the bulb and with a small flask.

Pl. 5, Figs. 5 and 6, show the phenomenon, the pressure of the mercury vapor being recorded on each photograph in the case of the bulb. I made a calculation by elementary methods of what was to be expected when the resonators became more closely crowded together, and came to the conclusion that such a drawing-in or contraction of the glow was not to be expected, but that what would actually occur would be a gradual diminution of the intensity of the glow, which at low pressures is spread uniformly over the illuminated wall, and a simultaneous increase in the intensity of the small image reflected from the inner wall. I now prepared a new bulb, which had never been heated or used in any experimental work, and found no trace of the contraction of the glow. A careful examination of the old bulb and the flask in a strong light revealed the presence of a slight amount of devitrification of the inner surface, the reflected image of the sun appearing surrounded with a fairly bright halo. This circumstance at once explained the contraction of the glow with increasing vapor pressure. As the density of the mercury vapor increased, the reflecting power of the inner wall increased, much as if a deposit of a metal was being gradually thrown down upon it, and this increase of the reflecting power was sufficient to develop the diffraction halo due to the slight roughness of the inner wall. The fact that the contracting glow usually had a definite though irregular shape, and was frequently accompanied by neighboring patches of lesser intensity, made me suspicious of the phenomenon in the beginning, but it was not until I noticed the slight devitrification of the surface that I was able to give a satisfactory explanation of the thing. On Plate 5, Fig. 6, the last impression (the fifth) was taken after the mercury arc had been burning for half a minute, and no longer emitted the exact frequency for which the mercury molecules responded. The reflection in this case is due wholly to the quartz, and we see only the two minute points of light previously referred to.

The real phenomenon is shown in Plate 5, Fig. 7, made with the clean bulb. *A* and *B* were taken at room temperature, the

former with a five-second exposure, the latter with one of half a second, to bring out better the relative intensities of the two images reflected from the inner and outer walls. I threw these out of focus a little, so that their relative intensities could be better determined. They appear expanded into circles of light due to zonal errors of the lens. It is clear that at room temperature the lower circle is much brighter than the upper, which was the one reflected from the inner wall. This is doubtless due to the fact that fused quartz is not perfectly transparent to the ultraviolet, and the light which gives rise to the image reflected from the inner wall twice traverses the quartz wall which was rather thick. The other pair of circles are reflected from the back wall, and disappear in the other pictures owing to the failure of the radiation to penetrate to the back. Pictures *C* and *D* were made with a pressure of mercury vapor of about 20 mm. The glow is now confined to that portion of the wall which receives the direct rays, and the image formed by the outer wall is still brighter than that formed by the inner, the ratio being about the same. *E* and *F* were made with a pressure of very nearly one atmosphere. The diffuse glow has entirely disappeared, and there remain only the two regularly reflected images, the upper circle now being distinctly brighter than the lower. That this image (the upper circle) really came from the inner wall was proved in the following way. The heated bulb was cooled on the illuminated side by a blast of air. This caused a very fine "dew" of mercury globules to condense on the wall, practically silvering it on the inside. A photograph was immediately taken and the upper circle of light was found to be the brighter of the two, as was the case with the dense mercury vapor. The diffuse reflection (resonance radiation) begins to weaken at a pressure of about 2 cm. (mercury vapor) and is practically gone at 70 cm.

POLARIZATION EXPERIMENTS.

Inasmuch as I have discovered strong polarization in the fluorescent light emitted by sodium, potassium, and iodine vapor,

I fully expected to find it in the case of the mercury resonance radiation, as the mechanism of the emission would appear to be much simpler in this case than in the other cases where we have, in addition to the resonance radiation, other associated frequencies emitted, which give rise to what I have named resonance spectra. No trace of any polarization could be detected with a Babinet compensator or Savart plate mounted in front of the resonance lamp. A small Foucault prism was used as an analyser, as ordinary Nicol's prisms are opaque to the ultra-violet on account of the Canada balsam with which they are cemented. Photographs showed no trace of the fringes which prove the existence of polarization.

EXPERIMENTS WITH THE RESONANCE LAMP.

The radiation emitted from the exhausted quartz bulb is so homogeneous, that a layer of mercury vapor 5 mm. thick and at the pressure which it has at room temperature (0.001 mm.) reduces its intensity by about one half. Various investigations with the vapor at exceedingly low pressure at once became possible. It is as if we had a gas which appeared quite black even at pressures commonly employed in vacuum-tubes. It will be possible to study the rate at which the vapor diffuses into other gases at low pressures, and it may be possible to tell in this way whether the resonators are in reality mercury molecules or larger aggregates.

I made two photographs which illustrate what a sensitive detector of small traces of mercury vapor we have in the light of the resonance lamp. A quartz bulb having an internal diameter of 1.5 em., containing a drop of mercury, was mounted in front of a photographic plate in a dark box and illuminated with the light of the lamp. The bulb cast a shadow as black as ink. The bulb was now opened, the mercury drop removed, and the bulb washed out with nitric acid and distilled water, heated nearly red-hot and a blast of air blown into it, and again photographed. It still gave the black shadow, though not as black as

before. It was only by prolonged heating to a red-heat and much rinsing out with an air current that I was able to obtain a shadow picture which showed the flask transparent. The flask had been previously heated until the mercury vapor in it had a pressure of several atmospheres, and I imagine that the inner surface may have adsorbed some of the vapor, which was not removed by the acid. A chemist would undoubtedly have called the flask clean, after the first treatment which I gave it. The two photographs are reproduced on Pl. 6, Fig. 9 with the flask full of mercury vapor at room temperature and Fig. 10 with the flask empty.

I next drilled a shallow cavity in the end of a brass cylinder, warmed it to a temperature of perhaps ten degrees above the temperature of the room, and placed a drop of mercury in the cavity, the drop standing up above the level of the end of the cylinder. This was photographed in the dark box by the light of the resonance lamp, and the picture showed the black column of mercury vapor carried up by the convection current of warm air (Pl. 6, Fig. 11).

I have set up a Michelson interferometer with a fluorite plate coated with a cathode deposit of gold for the purpose of ascertaining how large a difference of path is possible in the case of interference fringes formed by the light of this lamp. I imagine that the light may turn out to be more homogeneous than that of any other source with which we are acquainted. Of course it is possible that the line itself is complex, in which case matters will be different. The dispersion of the vapor in the vicinity of the 2536 line has just been investigated with the same apparatus and is reported in a following paper. It will be interesting also to place the resonance lamp in a powerful magnetic field, and study the Zeeman effect for a gas radiating by resonance instead of under the action of an electrical or other stimulus.

It even appears possible that the electric analogy of the Zeeman effect can be detected with the resonating mercury vapor, since it can be brought to a high luminosity in a vacuum which is

practically non-conducting, that is if the vapor does not become conducting when excited by the ultra-violet light, which I doubt; for a roughly carried out experiment with a small gold-leaf electro-scope showed no conductivity when the vapor in the bulb between two electrodes was excited. We cannot infer from this what it would do with a potential sufficient to give say a 20 cm. spark in an alternating spark-gap, but I have a feeling that the vacuum would support it.

In fact a very wide field of investigation appears to be opened by the discovery of the very remarkable behavior of the vapor of mercury at very low pressures.

This paper forms the third of a series upon the optical properties of mercury vapor, the first, being upon the fluorescence, etc., of the vapor;³ and the second, on the selective reflection of monochromatic light by mercury vapor.⁴ The investigation has been made possible through a grant from the Rumford fund of the American Academy of Arts and Sciences, and my thanks are due to the members of the Rumford committee for their generous aid.

¹ Phil. Mag., vol. xviii, p. 240.

³ Tom. cit., p. 187.

NO. 4.

THE SELECTIVE DISPERSION OF MERCURY VAPOR AT THE 2536 ABSORPTION LINE.

Up to the present time no quantitative determinations have been made of the selective dispersion of non-luminous absorbing gases. About ten years ago I made a somewhat detailed study of the dispersion of sodium vapor, and a good deal of work has been done since by other observers, working along similar lines, but in the case of this vapor no one has succeeded in working under conditions of known density, for the vapor cannot be bounded by transparent solid surfaces on account of the chemical action which it exerts. Ladenburg and Loria's determinations of the dispersion of hydrogen at the α and β lines are not open to this objection, but in this case the absorption and dispersion results from the circumstance that the gas is ionized and rendered luminous by the electric discharge, and the conditions are consequently a little more complicated.

A number of years ago I made some observations of the anomalous or selective dispersion of mercury vapor at the ultra-violet absorption line the wave-length of which is 2536. This vapor appeared to be an ideal medium for a quantitative investigation of the phenomenon, since it can be contained in transparent vessels of fused quartz, and its vapor density at various temperatures is very accurately known. As it seemed desirable to work with very low vapor densities, the interferometer method was the only one well adapted to the work, and I ordered from Heræus a tube of fused quartz 10 cm. in length, terminated with end plates of the same material, which had been ground and polished, and were fused to the ends of the tubes. This tube is shown in Fig. 1 of my paper on the Selective Scattering, etc.,

of Mercury Vapor (No. 3). It contained a drop of mercury and was very highly exhausted and sealed.

For the ultra-violet interferometer I had Mr. Petitdidier, of Chicago, prepare for me a plane-parallel plate of white fluorite, as it was feared that the double refraction of quartz would give trouble. Fused quartz would perhaps answer the purpose if it could be obtained free from *striae*, but as it was my intention to carry on other investigations with the instrument in the remote ultra-violet, I decided upon fluorite. Some difficulty was found in getting a good deposit of silver on the plate, and a cathode deposit of gold was accordingly used. The back mirrors of the Michelson interferometer were of speculum metal, and no compensating plate was used. The quartz tube was introduced into the optical path of the instrument in which the compensator is usually placed, and the two end plates which closed it very nearly equalized the two paths, as their combined thickness was very nearly equal to that of the fluorite plate. It proved to be quite a problem to heat the tube without at the same time heating the instrument, or the air in its vicinity, for the former would have caused a slow drift of the fringes, and the latter a fluttering confusion of them, either of which would have made photography impossible. The sodium tubes in the earlier work gave very little trouble, as it was necessary to heat only the central portion of the tube, which was done by an electric current. In the present case it was of course necessary to have every part of the tube, including the end windows, at the same temperature, and it seemed at first impossible to do this and at the same time keep currents of warm air out of the optical paths of the instrument. The problem was finally solved in a very simple manner. An air bath was constructed of the form shown in Fig. 1, out of two large brass tubes, one fitting within the other with a clearance of about a centimeter all around. Two small tubes were soldered into the ends of the outer tube, one of which was put in communication with an aspirator pump, and the other with a glass tube which was heated by a Bunsen burner turned down low.

The temperature of the inner chamber could be very nicely controlled by varying the height of the burner and the rate of flow of the water in the aspirator. For higher temperatures the flame was placed just below the aperture of the glass tube, so that the hot products of combustion were drawn through the air bath.

It was found that the temperature could be held constant, or rather within half a degree, for fifteen minutes or more, and as exposures of two or three minutes were all that were necessary, this arrangement gave entire satisfaction. The air bath was

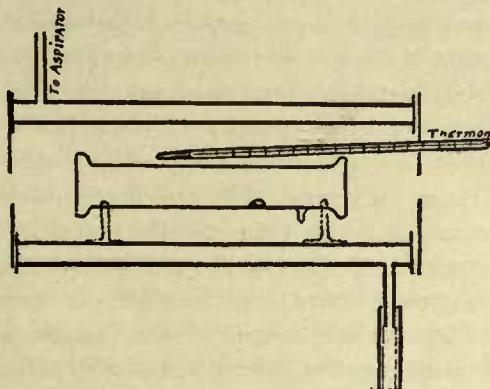


FIG. 1.

wrapped up in cotton, and discs of black paper, each perforated with a hole 1 cm. in diameter, were placed over the ends. The beam of light passed through these holes, traversing the quartz tube, which was mounted at the center of the air bath. As I do not remember to have seen any account of interferometer work in the ultra-violet, brief mention of some of the difficulties may be helpful to others taking up work along similar lines. The source of light was the iron arc, which was rendered parallel or slightly convergent for the ultra-violet, by means of a quartz lens. The fringes were first found with sodium light and the center of the system found in the usual manner with a small gas flame.

The mirrors of the instrument were adjusted so as to give a system of four or five horizontal fringes across the field of the instrument, which was of course somewhat constricted by the perforated screens of black paper, used to prevent as much as possible the escape of currents of hot air from the air bath. The iron arc was now placed in position behind the sodium flame and its light focused upon the back mirrors of the instrument by means of a quartz lens. An image of the fringe system was now projected upon the slit of a quartz spectrograph by means of a quartz fluorite achromatic lens. This gives us a spectrum of the arc traversed by horizontal black lines (the interference fringes) and if we have perfect compensation of the optical paths, and are at the center of the system the fringes will run in a horizontal direction throughout the entire spectrum. As a matter of fact it was found that no fringes at all were visible in the ultra-violet region and that they sloped in a very oblique direction in the violet, the slope increasing with a decrease of wave-length. This circumstance is due to the use of the two quartz end plates as a compensator for the fluorite plate: the dispersion of the two substances is quite different and the thickness traversed is not the same. The movable mirror of the instrument was now moved back a little and a second photograph taken. Matters were now worse than before, so the mirror was advanced a little ahead of the position which it occupied (perhaps 200 wave-lengths) when the colored fringes were visible with white light. The fringes could now be followed through the entire spectrum, though they were very oblique at the extreme ultra-violet end. A further advance of the mirror brought them approximately horizontal in the region of the 2536 line of mercury, where all of the work in the present case was to be done. Viewed with an eye-piece the spectrum now showed nearly vertical fringes in the red and orange, and very oblique ones in the yellow and green.

A rather poor photograph of the entire spectrum is reproduced on Plate 7, Fig. 9, which however gives a fair idea of the change in

the slope of the fringes with change of spectral range. At the right-hand end of the picture (blue) the fringes slope down to the right at an angle of about 45° . In the middle (upper ultra-violet) they are horizontal, while at the left (lower ultra-violet) they slope down to the left. This method of studying dispersion was first used by Puccianti in his study of the vapors in metallic arcs. It has the advantage of giving us a photographic record of the retardations or accelerations, as we may for convenience term them, of waves of various lengths in the vicinity of absorption bands. In the present case we are dealing with a single absorption band only, the 2536 line of mercury, which fortunately falls in the middle of a group of strong iron lines. When mercury vapor is formed in the quartz tube, the fringe systems in the various iron lines are shifted by different amounts, and in different directions. A photograph of the iron spectrum in coincidence with that of the quartz mercury arc, in the region under investigation, is reproduced on Plate 7, Fig. 7. The mercury line which gives rise to the selective dispersion is indicated by a long arrow, and the fainter companion line which borders it on the short wave-length side by a short one. Curiously enough this faint companion line does not show any evidence of its existence in the absorption spectrum, though there is a faint absorption line on the other side of the main line at about the same distance from it, which I have found represented by a bright line in the fluorescence spectrum of the vapor excited by the light of the cadmium spark. A photograph of this spectrum will be found in the second edition of my *Physical Optics*, on page 580, in which the 2536 fluorescent line will be seen to be accompanied by a faint companion on the long wave-length side. The negative, of which Fig. 7 is a sixfold enlargement, was made with a large quartz spectrograph by Fuess which was placed at my disposal by Professor Trowbridge, of Princeton University. It has lost much in the process of enlarging, for on the original the iron line immediately to the right of the mercury line is a beautifully resolved double line.

The wave-lengths of the two mercury lines were measured with reference to Rowland's values given for the iron lines, the main line being 2536.5, and the faint companion 2534.8.

The wave-lengths of the iron lines immediately to the left and right of the main mercury line, which are the lines in which the greatest displacement of the interference fringes occur are 2535.6 and 2536.9. Inasmuch as the mercury line is much nearer the latter, it is in this line that we should expect to observe the greatest displacement of the fringes, for a given vapor density. Over 100 plates were exposed with the tube at various temperatures between 23° and 60°. It was found impossible to work at higher temperatures, for the fringes became very indistinct in the vicinity of the absorption line. This results from the circumstance that one of the interfering beams is weakened by absorption, and interference then takes place between two beams of unequal intensity: moreover it was more difficult to hold the temperature constant during the time of exposure at the higher temperatures. The pictures are scarcely suitable for reproduction as they were made with a small quartz spectrograph, the only instrument at my disposal, nevertheless the five enlargements reproduced on Plate 7, Fig. 10, will serve to give a general idea of the distortion of the interference fringes in the vicinity of the 2536 mercury line. The temperature of the mercury dispersion tube is recorded on each photograph. The position of the mercury 2536 line is indicated on the first picture by an ink mark. On some of the plates there was an indication of a slight displacement of the fringes in the iron line immediately to the right of the mercury line even at room temperature (23°). It is very slight however, certainly not more than 0.1 of a fringe width. At 35° the displacement becomes very noticeable, amounting to about a quarter of a fringe width. At this temperature the pressure of the mercury vapor is 0.004 mm. or four times the pressure which it has at room temperature. The length of the quartz dispersion tube being ten centimeters we can definitely state that light of wave-length 0.4 of an Ångström

unit longer than that of the absorption line is retarded 0.25 of a wave-length in traversing a column of the vapor 20 cm. in length, (since the light traverses the tube twice). It was expected that the fringe shifts would increase proportionally with the vapor pressure, but this was found not to be the case, for at a temperature of 58° , at which the pressure is 0.0215 mm., or five times as great as at 35° , the displacement of the fringes in this same iron line is only 0.6 of a fringe width, whereas if the retardation was proportional to the pressure we should expect a displacement of 1.25 fringe widths. It was thought at first that a mistake might have been made in the identification of the fringe under observation, and that the displacement might be 1.6 instead of 0.6, but an examination of a very large number of photographs taken at intermediate temperatures showed that no error had been made. The displacements of the fringes in the various iron lines for the vapor at different temperatures were measured as carefully as possible on the dividing engine, and are given in the following table. The wave-lengths are as follows:

Iron Line No. 1	2535.6
Mercury Line	2536.5
Iron Line No. 2	2536.9
Iron Line No. 3	2539.0

SHIFT IN FRINGE WIDTHS.

Temp.	Pressure, mm.	No. 1.	No. 2.	No. 3.
32	0.0031	0.16	0.25	—
41	0.0062	0.25	0.34	—
45	0.0096	0.30	0.40	0.11
50	0.0122	0.40	0.55	0.18
58	0.0215	0.50	0.65	0.25

It is clear from this table that the refractivity of the vapor, or rather that part of it due to the absorption line in question, does not increase in proportion to the vapor density. It appears therefore very doubtful whether this absorption line is due to the normal mercury molecule. We may call it the dispersing

molecule, which may either be an atomic complex, or a molecule in a state of ionization, and it seems probable that these exist in small numbers in comparison to the normal molecules. At all events the percentage of molecules in this condition is less as the vapor pressure increases, for as the table shows, a sevenfold increase in pressure only triples the action on the wave velocity for Line No. 1, and scarcely more than doubles it for Line No. 2.

I feel a little disappointed with the results as a whole, as I had hoped to secure records over a much wider temperature range, dealing with shifts amounting to many fringe widths, but this appeared to be impossible with the arrangement of apparatus adopted. It is a great pity that we do not have some method intermediate in point of sensitiveness between the interference methods and the prism. It is doubtful whether reliable results could be obtained with a prism of mercury vapor, since we should have to use one with a base of 20 cm. to obtain a retardation of half a wave-length across the entire wave-front at a temperature of 58° . I have, however, obtained fairly good photographs of the selective dispersion at the 2,536 line by employing a long tube of steel similar to the ones used with sodium, but as we are dealing in this case with non-homogeneous vapor, the method is wholly unsuitable for quantitative measurements. The results given in this paper, while not as satisfactory as I had hoped for, appear to me to be of some interest in that they have pretty clearly established the fact that not all of the molecules are concerned in the dispersion, and consequently in the absorption. Some time during the coming winter I plan to investigate the absorption of the vapor quantitatively at different pressures and densities. The results obtained in the study of the dispersion would lead us to expect that with a given amount of mercury vapor we should have more powerful absorption as we reduced the pressure, which is precisely the opposite of what is usually observed. The very homogeneous light from the resonance lamp, described in one of the previous papers (No. 3), will greatly facilitate this study.

NO. 5.

RESONANCE EXPERIMENTS WITH THE LONGEST
HEAT-WAVES.

In the autumn of 1910 H. Rubens and R. W. Wood succeeded in isolating and measuring the longest heat-waves known at the time, by a method based on the circumstance that the refractive index of quartz is much higher for these waves, than for light waves and the shorter heat waves. A description of the method, which may be termed "focal-isolation" will be found in my *Physical Optics*, 2d edition (1912). The waves were emitted from a Welsbach mantle and had a wave-length of over one tenth of a millimeter (112μ) and Rubens and Von Baeyer subsequently obtained by the same method waves of greater length (0.3 mm.) from the quartz mercury arc. As the shortest electric waves obtained by Von Baeyer have a length of about 2 mm. it will be seen that the gap between the electric and optical spectrum is very nearly filled up.

The very great length of these heat waves makes it possible to try experiments analogous to the experiments made by various investigators on the action of metallic resonators on electromagnetic waves. I have already commenced an investigation of this subject, and the results obtained up to the present time will be reported in this paper.

The first experiments were made with very minute particles of metallic copper deposited on quartz plates. The metal can be obtained from the chemists in the form of a very fine powder, and if some of this is violently shaken in a tall glass jar, the finest particles remain suspended in the air. If the jar is then inverted over the quartz plate, and allowed to stand for a few minutes, a beautifully regular deposit settles on the plate. Treating the plate to the process four or five times builds up a deposit which

is almost opaque to light, the slight amount which struggles through being of a greenish color. To my surprise I found that even these very heavy deposits, which by actual measurement transmitted only two or three per cent. of visible light, were perfectly transparent to the long heat waves. The same amount of metal, in fact a much less quantity, in the form of a uniform film would be absolutely opaque to the heat waves, for we know that the reflecting power of a metal is practically 100 per cent. for all waves longer than about 10μ . The same thing is true of carbon deposits. When studying the transmission of the waves through various substances in collaboration with Rubens, it was found that a deposit of smoke on a quartz plate, so dense that the Welsbach mantle was invisible through it, transmitted over 95 per cent. of the heat radiation. It seemed of interest to ascertain the relation existing between the transparency of a layer of metallic particles, and the size of the particles, in other words, to carry out experiments analogous to those on the action of tinfoil strips of various size (mounted on glass) on electro-magnetic waves. Various methods may be used for the preparation of the resonator plates. We may deposit a film of the metal on a quartz plate and then rule it into small squares or rectangles with a diamond point, on a dividing engine. This method was tried over fifteen years ago by Rubens and Nichols; much shorter heat waves were then available (12μ) and though the experiments appeared to indicate electro-magnetic resonance, they were not as satisfying as was to be desired.

Another method is to prepare metal particles of uniform size and deposit these over the quartz surface.

This was the method first adopted in the present case. I first tried blowing a fusible alloy into a fine spray with an atomizer (the method used by Professor Millikan and J. Y. Lee).

Very perfect spherical droplets can be obtained in this way but difficulties were found in sorting them out into groups of uniform size of particles, and in depositing them (after sorting) with any regularity of distribution. It then occurred to me to

condense a metallic vapor on the quartz plates in the form of a "dew." This method worked admirably. A small quantity of mercury was heated in a beaker, and the quartz plate suspended in a horizontal position about 2 cm. above the surface of the metal. Very regular deposits were obtained in this way, the size of the globules varying with the duration of the exposure of the plate to the metallic fumes.

Photographs of the deposits taken with a microscope are reproduced on Plate 7, Figs. 1 to 6 inclusive. A photograph of a "stage micrometer" scale is reproduced immediately below the figures. One division on this scale corresponds to 0.01 mm. As is apparent from the photographs the diameters of the drops of a given deposit are fairly constant and their distribution is pretty regular.

The diameters are as follows on the plates photographed: Fig. 1 (.005 mm.), Fig. 2 (.01 mm.), Fig. 3 (.02 to .03 mm.), Fig. 4 (.03 to .04 mm.), Fig. 5 (.05 mm.), Fig. 6 (.06 to .08 mm.). Thus the smallest particles used had a diameter equal to about 1/20 of a wave-length, and the largest 2/3 of a wave-length. The transmission of each plate of resonators was compared with that of a clean plate of quartz of the same thickness, for radiation of wave-length 1μ , and the 112μ waves obtained by focal isolation. The transmission of the 1μ waves gives us a rough measure of the ratio of the covered to the uncovered portion of the surface, for the metal droplets act merely as opaque obstacles for these very short heat waves. The observations were made with Dr. Pfund's infra-red spectrometer, which he kindly placed at my disposal. The transmission of the 112μ waves was measured with a radiomicrometer of the same type as the one used in the experiments carried out in collaboration with Professor Rubens. The instrument was made for me by Herr Obst, the mechanician of the Berlin physical institute, but as it arrived with the thermo-electric junction damaged it was fitted up with a much lighter junction, which Dr. Pfund made for me, with perhaps 1/10 of the heat capacity of the original one. It proved far more sensi-

tive than the one used in the earlier work, giving about double the deflection for the same period, with the 112μ waves obtained under identical conditions. The transmissions of a number of resonator plates are given in the following table.

	% Transmitted of Radiation $\lambda = 1\mu$.	% Transmitted of Radiation $\lambda = 112\mu$.	Diameter of Spheres.
Fig. 1	45	100	.005 mm.
Fig. 2	26	95	.01
Fig. 3	32	82	.02-.03
Fig. 4	45	58	.03-.04
Fig. 5	26	50	.05
Fig. 6	30	27	.07-.08

This table shows us the droplets have no effect on the very long heat waves until their diameter exceeds about $1/10$ of a wavelength. When the diameter is about $\frac{1}{4}\lambda$, as in Fig. 4, the transmission is not much greater for the 112μ waves than for the short ones. For the case shown in Fig. 5 we have slightly larger spheres packed much closer together however, so that we have only 26 per cent. transmission for short waves; even now 60 per cent. of the energy of the 112μ radiation is passed by the plate. On a further increase of size, Fig. 6, the transmission is about the same for both wave-lengths.

It appears to me to be worthy of remark that in *no case* is the opacity of the resonator plate greater for the long waves than for the short, in other words, each sphere is able to stop only that portion of the energy of the wave-front which falls upon it, and does not drain the region surrounding it. This rather surprised me for I had expected to find that with spheres of a certain size we should have moderate transparency for short waves and absolute opacity for the long ones.

I have been unable to find any investigation, either theoretical or experimental, of the action of spherical metal obstacles arranged in close proximity, upon electromagnetic waves, so that there is nothing with which to compare these results at the present time.

Investigations have, however, been made with linear rectangular resonators, and I accordingly commenced experimenting with these. Silver was deposited on quartz and ruled into small squares with a dividing engine, but I found that the film was quite as opaque to the 112μ waves after the cross ruling, as before, though the size of the squares was less than $1/10$ of the wavelength. A photograph of the film with one set of rulings is reproduced on Plate 7, Fig. 8. This I have alluded to in a subsequent paper (No. 9). It was found that the ruling had not altered the conductivity of the film, though the microscope indicated that the diamond had cut clear through the silver down to the quartz. If the conductivity is not affected we should not expect the opacity of the films to be decreased. The question as to why the conductivity is not affected will be discussed in the subsequent paper. In order to obtain satisfactory results with resonators prepared in this way, it will be necessary to devise a way of making wider cuts, and leaving less metal between them, and experiments in this direction are now in progress.

Garbasso in his book gives the wave-length emitted by a spherical oscillator as 3.6 times the diameter of the sphere.

There is no difficulty in forming mercury drops with a diameter of 2μ or less, consequently we might expect some selective in the region around 10μ .

Professor Trowbridge, of Princeton, has taken some bolograms with his infra-red outfit, which records to 12μ , and has failed to find any selective action in this region. Experiments with spherical resonators and short elective waves are much to be desired, and I trust that some investigator equipped with suitable apparatus will experiment with coarse bird-shot fastened to a glass plate with paraffin.

NO. 6.

DIFFRACTION GRATINGS WITH CONTROLLED
GROOVE FORM AND ABNORMAL
DISTRIBUTION OF INTENSITY.

In the Philosophical Magazine for September, 1902, I published an account of a diffraction grating, ruled on speculum metal, which exhibited a most remarkable distribution of intensity of the energy in some of the spectra. The continuous spectrum of a white source was interrupted by bright and dark bands sometimes not over 20 or 30 Ångström units in width, which appeared most distinct when the direction of the electric vector was perpendicular to the direction of the groove, and vanished when these directions were parallel.

In the present paper I shall describe a still more remarkable grating which shows a bright *line* in the continuous spectrum of a white source, which by actual measurement is only 3 Ångström units in width, *i. e.*, of a width equal to one half of the distance between the D lines. As the angle of incidence is varied the position of the bright line in the spectrum changes, and, what is of especial interest, its wave-length corresponds exactly to the wave-length which is just passing off from the grating at grazing emergence in the fourth order spectrum. This is in agreement with the surmise expressed by Lord Rayleigh,¹ that abnormalities are to be expected at such angles of incidence that spectra of higher orders are just passing off. The bright line in question appears in the first order spectrum on the opposite side from that on which the grating concentrates light, and is about as bright as the continuous spectrum upon which it appears projected, so that the brilliancy at the point in question is about

¹ Phil. Mag., July, 1907.

double that of the rest of the spectrum. In viewing the spectrum of the arc, the bright line resembles the bright lines which sometimes flash out upon the continuous spectrum of the crater.

As I showed in my paper upon the echelle grating,² if a grating is ruled upon a polished surface of a soft pure metal instead of on a hard alloy such as speculum metal, the form of the groove can be made to conform more perfectly to that of the ruling point, which moreover does not wear away rapidly as is the case when the ruling is done on a hard alloy. In the case of the echelle gratings I used a surface of gold-plated copper, which gave such excellent results that I immediately tried to find a surface suitable for optical gratings. A very thin coating of silver was deposited upon a plate of polished speculum metal by electrolysis, and was then very carefully polished. This was found to serve admirably, and a trial grating, with 14,438 lines to the inch, was ruled with the old Rowland machine, which showed a very dark central image and a very bright first order spectrum. Spectra were also obtained on plates prepared in this way which yielded spectra in which certain colors were wholly absent, the dark bands reminding one forcibly of the dark bands observed with the curious grating described in 1902, except that they were much wider.

Dr. Anderson, who has had charge of the dividing engines, informed me that he had found a diamond point which ruled gratings showing anomalies similar to those which I described in the earlier paper, and he has ruled me a number of gratings upon a thin silver surface deposited upon a speculum plate. The lines are ruled at the rate of 10,000 to the inch on the so-called 20,000 machine. The first order spectrum on one side is very bright, while that on the other is quite faint, and it is in this faint spectrum that the abnormalities are found. This grating appears to be of such good quality that it seems probable that excellent optical gratings of very large size can be made in this way. We can choose our metal according to the region in which

² Phil. Mag., Oct., 1910.

we wish to work. Gold, for example, would be far better than speculum metal for the region between 5500 and 8000, for gold reflects 90 per cent. in the red, while speculum metal reflects only 65 per cent., a matter of some importance for example in the study of the resonance spectra of iodine, which are not very bright and fall exactly within this region.

Gratings made in this way would have to be handled very carefully, however, for I have found that the lightest possible rubbing with soft chamois skin alters the distribution of the light in the spectra in a most remarkable manner. It is possible in this way to raise the intensity of the faint first order spectrum four- or fivefold and cause the dark bands to disappear entirely. It is quite interesting that the groove form can be thus "figured" after the grating is ruled, though I doubt whether the efficiency of a grating could ever be improved in this way, since the tendency seems to be always to give a more uniform distribution of light among the spectra, which is precisely what we do not want. This "figuring" of the groove has, however, proved of value in the study of the bright and dark bands as they can be developed in intensity in this way, and caused to change their position in the spectrum.

While the present study has not completely solved the question of the cause of the remarkable anomalies, many additional experimental data have been obtained, and it is possible that the results may point to the modifications necessary to make Lord Rayleigh's theory cover the ground.

I shall now describe in detail the observations made with one of the gratings. The groove form is probably quite similar to that used in the case of the echelle gratings, one side very steep, the other making only a small angle with the original surface. This is similar to that of the grating described in 1902, from which I made a cast at the time with celluloid deeply stained with an aniline dye, which was sectioned with a microtome and examined under the microscope. The grating was mounted on the table of a large Fuess spectrometer so arranged

that the table turned with the graduated circle. At normal incidence it showed a black band in the red about 30 Ångström units in width, the centre of which was at 6560, and a bright line 3 Ångström units wide at 6400.

The telescope and collimator were not used, the spectrum being viewed by the eye directly. The source of light was a Nernst filament situated at a distance of about 3 meters from the grating, with a very brilliant neon tube immediately behind it. A Nicol prism was mounted in front of the lamp, for the bands appeared at their best with polarized light (electric vector perpendicular to the grooves). Behind the neon tube an arc lamp was mounted for producing the very intense illumination necessary for the experimental determination of the wave-length of the light passing off from the grating at grazing emergence. On viewing the spectrum in the grating, the dark band or the bright line could be brought into coincidence with some one of the numerous bright neon lines, by changing the angle of incidence.

As a check on this method of determining the position of the bands the arc was lighted, and a Schmidt and Haensch pocket-spectroscope, provided with an illuminated scale of wave-lengths, was directed at the spectrum seen in the grating. The dark band then appeared in the spectrum seen in the small spectroscope, and its wave-length could be read off at once. The width of the bright band was determined with the large spectrometer with fixed telescope and collimator of 2.5 meters focus, by comparison with the D lines.

Considering the grating mounted as in Fig. 1a, the faint first order spectrum in which the abnormalities are seen is viewed in the direction *A*. The first order spectrum on the other side (direction *B*) is extremely bright, being favored by the broad, gently sloping sides of the groove. The spectra passing off at grazing emergence are very bright in the direction *C* and very faint in the direction *D*, as is to be expected, for the steep, narrow sides of the groove favor the direction *C*. The circle of the spectrometer was set at zero, and the grating turned on the table

until the incidence was normal, as determined by reflecting the image of the ruled spot back to the arc.

The spectrum seen in the direction *A* exhibited a dark band in the red and a very faint narrow bright band in the orange. Previous experiments with another grating have shown that

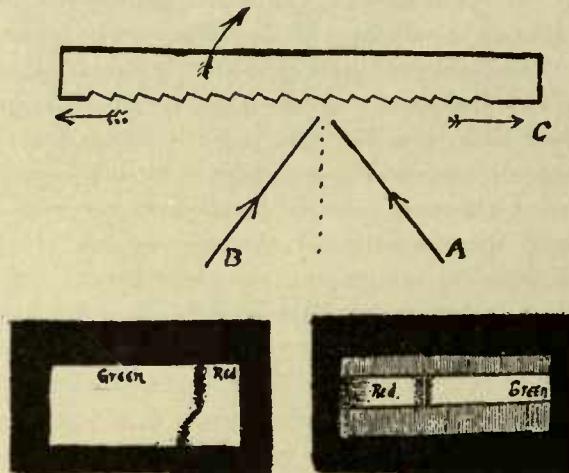


FIG. 1.

lightly wiping the surface modified the appearance of the bands, and an attempt was made to better them in the case of this grating. A very light rubbing with a powder-puff made of swan's down increased the blackness of the dark band and increased the narrowness and intensity of the bright band, which presently with a little further rubbing, became a line. The lower corner of the grating was now rubbed lightly with chamois skin. This operation obliterated all trace of the bright line, and caused the dark band to shift into the yellow-green region. If the spectrum was made to cover the entire surface of the grating by bringing the source of light nearer, the dark band in the red was seen to pass gradually into the green region, the band appearing curved, as shown in Fig. 1, *b*. In this figure the lower right-hand corner of the ruled surface has been rubbed with chamois skin.

The relations between the positions of the bright line and dark band and the angles of incidence were now determined. The circle was turned so as to rotate the grating in a clockwise direction (Fig. 1, *a*) through an angle of 11° . The dark band moved from the red down into the green, preceded by the bright line which remained distinct up to a rotation of 9° but disappeared at 11° . Its disappearance may have been due to its having passed into the blue region, in which the eye cannot see as sharply as in the more luminous regions. In the following table are given the positions of the bands for various angles of incidence. The wave-lengths passing off at grazing emergence in the direction *C* are given in the fourth column.

Incidence Angle.	Dark Band.	Bright Line.	Passing Off.
11°	5500	5150
9°	5650	5340	5340
$6^\circ 20'$	5900	5650	5650
$4^\circ 55'$	6000	5800	5800
$3^\circ 55'$	6100	5940	5940
$2^\circ 50'$	6200	6030	6030
$1^\circ 30'$	6400	6200	6200
0	6560	6350	6350
$1^\circ 10'$	6650	6520	6520
$1^\circ 50'$	6600	6600	6600
$2^\circ 40'$	6720	6720

As will be seen from this table, the wave-length of the bright line agrees in each case with that of the light which is passing off the grating in the fourth order. As the grating is turned in a clockwise direction the two bands move towards the region of greater wave-length, the bright line a little more rapidly, until at an angle of $1^\circ 50'$ on the other side of normal incidence the bright line moves into the centre of the dark band, appearing as shown in Fig. 1, *c*.

This entrance of the bright band into the dark one is very interesting, and should be a valuable clue to the origin of the bands. The wave-length of the dark bands, for in the case of some of the gratings several dark bands appear, bears no relation

to that of any of the colors which are passing off the grating at grazing emergence, though in general they seem to correspond to wave-lengths diffracted at angles a little greater than grazing emergence; in other words, to result from disturbances which come from the steep side of the groove and are reflected against the opposite side.

It was found that certain anomalies appear when the direction of the electric vector is parallel to the groove. For example, if we hold the Nicol in front of the eye and allow unpolarized light to fall upon the grating, the dark band appears in the orange (incid. angle 5°) when the short diagonal of the Nicol is horizontal, *i. e.*, when the electric vector is perpendicular to the groove. If now we rotate the Nicol through a right angle the entire red end of the spectrum above the dark band disappears, the portion of the spectrum vanishing in this case being at least five or six times the width of the dark band.

A study was also made of the polarization of all of the spectra and the central image. Though I doubt if these data will prove of material assistance in the development of a theory accounting for the bright and dark bands, I will include them for the sake of making the study as complete as possible.

The grating was set at normal incidence which brought the dark band to wave-length 656. The incident light was unpolarized, and the spectra examined through a Nicol. In the first order spectrum all of the light on the red side of the dark band was polarized \perp , the rest of the spectrum showed an excess of $=$ polarization. In the second and third orders on the same side, the red end was nearly completely polarized $=$, the remainder showed an excess of \perp polarization. The fourth order was completely polarized $=$.

On the other side of the central image the very bright first order spectrum showed little or no trace of polarization. In the second order the red end was completely polarized \perp . Third order no polarization, and fourth order all \perp . The central image, examined with a spectroscope, showed a dark band at 650, and

all longer waves were found to be polarized \perp as in the faint first order spectrum. The \perp and $=$ signs referred to above denote the direction of the electric vector with respect to the direction of the groove.

It is a matter of some importance to ascertain what becomes of the light which is absent in the spectrum. If one spectrum shows a dark band we should expect some other spectrum to show a bright band at the same point. This, however, is not the case, and we may infer from this that the absent energy is distributed amongst the other spectra, the amount received by each being too small to be noticeable.

It appears to me that the present paper contains sufficient experimental data to thoroughly test any theory which may be developed to account for these remarkable anomalies. It seems evident that they are to be referred to the action of the sharp ridges and not to the bottoms of the grooves, as they are profoundly modified by the lightest possible rubbing of the grating with soft chamois skin.

The extraordinary narrowness of the bright line (3 A. E.) undoubtedly requires the coöperation of a large number of lines, and it is to be noticed that its wave-length agrees exactly with that of the light which is passing off the grating on the side towards which light is reflected from the steep sides of the grooves. It is worthy of remark that the tops of the ridges will be illuminated by diffracted light of the right wave-length, though this circumstance alone is not sufficient to account for the narrowness of the bright line. The shift of the dark band towards the region of shorter wave-lengths produced by lightly rubbing the surface of the grating should prove an important clue, as well as the unequal rate of advance of the bright line and dark band along the spectrum as the grating is rotated.

If any further experiments are required to test any theory which may be developed, they can be made without difficulty.

NO. 7.

NICKELED GLASS REFLECTORS FOR CELESTIAL
PHOTOGRAPHY.

The failure of silver to reflect well in the ultra-violet region, places a limit to the extent of the spectrum of a star or other celestial object obtained with a reflector of the ordinary type. As is well known, the spectrum of light which has penetrated the earth's atmosphere extends to about wave-length 2900. In the region around wave-length 3160 silver reflects only 4 per cent. of the incident light; in other words, the silvered mirror is no more efficient in this region than unsilvered glass. For extending the work which I commenced two years ago on the ultra-violet photography of the moon, it became necessary to construct a long-focus mirror of large aperture capable of reflecting copiously the light transmitted through the silvered-quartz ray-filter. The great weight of a large mirror of speculum metal, and difficulties in its construction, with its liability to tarnish, led me to try to work out some method of depositing a film of some suitable metal upon a glass mirror.

Consulting Rubens's tables of the reflecting power of metals, it appeared that nickel would prove most suitable, its reflecting power throughout the entire spectrum being only a little less than that of speculum metal. So far as I was able to find, no method is known of depositing nickel chemically, except the process in which the gas nickel carbonyl is employed. This gas is extremely poisonous, and I understand that the metal films are bright only on the surface which is in contact with the glass. I accordingly determined to use this method only as a last resort, and commenced experiments at my East Hampton laboratory last summer on the electrolytic deposition. It was found that

solutions with an acid reaction either frilled or completely removed the silver film, which was deposited chemically to serve as a substratum for the electrolytic film. I commenced work with copper, and found that if a dilute solution of the sulphate was converted into cuprammonium by the addition of ammonia, a beautiful deposit could be thrown down in about 30 seconds with two dry cells. I then tried the double sulphate of nickel and ammonia. This gave some trouble at first, but it finally yielded good deposits. The solution must be very dilute, however, say 10 grams to the liter, and it is a good plan to add a little ammonia to it, sufficient to give it a very slight odor. From one to three dry cells can be used, according to their condition and the size of the mirror to be coated. The silver substratum should be thin enough to show a deep blue color when examined by a strong light, and the nickel should be thrown down until it becomes opaque. Some experience will be necessary before good deposits are obtained. If the silver coating is too thin, the fall of potential along the surface from the point where the battery wire joins it is too great, and the deposit is not uniform. It is a good plan to practice with small glass plates until one becomes familiar with the difficulties, and learns how to avoid them.

A nickel anode of about the same area as the plate to be coated is joined to the carbon pole of the battery, though in the case of my 16-inch long-focus mirror, I used a 16-inch disk of copper; it makes little or no difference which is used, as very little metal is thrown out of solution. Before depositing the nickel I at first dried the silvered mirror, and polished off the light deposit of dust which usually clouds the surface. This is a bad plan, for it is almost impossible to avoid long scratches, which cut through and destroy the continuity of the conducting film and result in an erratic distribution of the current; if this is the case, the nickel deposits along one side of the scratch only, and the deposit is very streaky. If the current is too weak or if the current is applied for an insufficient time, one obtains a very thin, yellowish deposit which has a very low reflecting power in the ultra-violet,

not much better than that of the silver. Continuing the process a little longer usually remedies this defect.

To study the reflecting power of the various films I reflected the light from the cadmium or iron spark from them into a quartz spectrograph, and obtained in this way spectrograms which enabled their behavior to be judged at once. On Plate 8, Fig. 1, we have two spectra of the spark of cadmium and tin, the upper, *a*, taken with the light reflected from a nickle-on-glass film, the lower, *b*, with a silver film. As is at once apparent, one region of the spectrum in the latter photograph is wholly absent, and the entire ultra-violet below this region is relatively weak. Fig. 2 shows the same thing with the iron spark. Spectrogram *c* is made with direct light of the spark transmitted through the quartz-silver ray-filter, and shows that the region which the silver fails to reflect is copiously transmitted. Fig. 3 is extremely interesting and shows the reflecting power of glass, silver, speculum metal, and nickel for various regions of the spectrum.

A shallow glass dish was silvered on the inside. The lower portion of this deposit was then nickel plated, and a portion of the silver wiped from the upper portion with a bit of cotton moistened with very dilute nitric acid. The clear glass is marked "*G*" on the pictures, the nickel "*Ni*," the silver "*Ag*," and the plate of polished speculum metal, which stands behind the dish, "*Sp.*"

The mirrors were mounted near an open window, at such an angle as to reflect the light of the sky to the camera, which was provided with a quartz lens. Photograph *A* was made with the quartz lens unsilvered, that is, chiefly through the action of the blue and violet rays. The silver and the speculum metal come out very bright, while the nickel is much darker, and the unsilvered glass spot *G* is practically black. *B* was made with the quartz lens coated with a film of silver of such thickness that a brightly lighted window appeared very deep blue through it. In this case we have a mixture of violet and ultra-violet in such proportion, that the silver, nickel, and speculum all reflect about

equally well. The dark V-shaped band which separates the nickel area from the silver is the thin yellow deposit above referred to, which diminishes the reflecting power in the ultra-violet. No trace of this appears in the first picture. In the small triangular area below the "*Ag*" the nickel deposit is thinner than over the rest of the lower portion of the plate, and the reflecting power is less. Photograph *C* was made through a silver film of such thickness that a brightly lighted window was barely visible through it, and the sun appeared as a disk of a bluish-white color easily supported by the eye. This picture is made chiefly by the ultra-violet region between wave-lengths 3000 and 3200. The silver reflects only very little better than the spot of clear glass, and the speculum somewhat more strongly than the nickel. In the case of *D* the silver film was so thick that the sun could be seen only as a feebly luminous ball of a deep violet color, resembling the lighted window as seen with the thinner film. A tungsten lamp was absolutely invisible through it. This is the best thickness to employ for ultra-violet photography. The glass and silver both come out almost black, the nickel fairly bright, and the speculum a little brighter.

It appears to me that there is a wide field of investigation open in various branches of science, by means of photography with these obscure rays. I have found that many white substances are absolutely black in this ultra-violet light, zinc-oxide being a conspicuous example. White garden flowers have very different reflecting powers in this region of the spectrum. Common phlox comes out coal black, while white geraniums are very much lighter. The earlier photographs which I made were taken with a silver film which was much too thin, as the investigations of the past summer have shown, and it is impossible to predict what will be found in the pictures of the moon and planets which are soon to be made with a very thick silver film and the long-focus nickel mirror.

We will now take up the method of coating a large mirror with a deposit of nickel.

The mirror which I have nickeled for the ultra-violet photography of the moon and planets is 16 inches in diameter and has a foetal length of 26 feet. It was made by Mr. John E. Mellish, of Cottage Grove, Wis., and is of very good figure. The silver substratum was thrown down by the formaldehyde process described in the following paper and the plate transferred to the nickel bath without drying, the surface, however, being first well washed under a rather heavy stream of water to remove as much of the sediment as possible. The deposition of the nickel was carried on in a cylindriical pan of galvanized iron, which I found in the local hardware store, the inner surface being coated with paraffine to prevent the solution from attacking the metal. The silver surface of the mirror was about an inch below the surface of the nickel solution, the anode consisting of a circular disk of sheet copper of the same diameter as the mirror. A short piece of heavy brass tubing was soldered to the center of the copper disk to serve as a handle, and the wire from the battery was twisted around this. A V-shaped notch about an inch in depth was cut in the margin of the disk to facilitate making contact with the silver film. The other wire from the battery was attached to a slender rod of brass with a scrap of platinum-foil soldered to its lower end. This piece of foil was crumpled up so as to make contact at many points with the silver. The copper disk was carefully immersed in the solution and held so as to be everywhere nearly at the surface. This insured a uniform distance at every point between the anode and the silver film. The platinum electrode was now brought in contact with the silver film by passing the brass rod down through the V-shaped notch, and the current was allowed to flow for thirty seconds, after which the mirror was removed and held up to the light. The film was much darker than before but not quite opaque. Thirty seconds more finished the operation and gave a beautiful coat, which was washed, dried, and rubbed lightly with cotton to remove the slight film of sediment.

If the current-strength and density of solution have been right, the surface of the nickel, as soon as it is removed from the plating bath, should appear bright, though distinctly duller than the silver. It is a good plan to prepare a small glass plate with half of its surface silvered and the other half никелед. In this way it is possible to judge of the quality of the nickel film, which should appear of about the same brightness as the silver film viewed through a nicol prism, which reduces the intensity of the reflected light by one-half. If the film appears yellow, or brownish, like smoked glass, something has gone wrong. If the silver peels from the glass or frills, the current has been too strong or it has been applied for too long a time. The coating which I have applied to my mirror is very nearly as bright as the surface of my 13-inch short-focus speculum. It may happen that the film appears to be all right until an attempt is made to clean it after it is dry, when it is found that the slightest rubbing with soft cotton strips the film from the glass. This is probably due to the fact that too much metal has been deposited.

As is well known, nickel deposited by electrolysis comes down under a tremendous tension. Even in technical work, where it is deposited on solid metal, it is apt to scale off if deposited too thickly. Under the circumstances, it is rather surprising that the silver film is able to stand up under the strain.

In addition to the advantage to be derived from the higher reflecting power in the ultra-violet, it is possible that the nickel film may prove more permanent in atmospheres contaminated with sulphur, though I have not had my mirror under observation for a sufficient length of time to be able to speak of its lasting qualities. One mirror which I prepared early in the summer appears to have changed, the surface having a crystalline appearance in spots, as if the two metals had alloyed. This mirror was made, however, before I had worked out the process to my satisfaction, the film being of the brownish color referred to above. The electrical process does not interfere with the figure,

102 NICKELED GLASS REFLECTORS FOR CELESTIAL PHOTOGRAPHY.

as the thickness of the layer deposited is but a very small fraction of the wave-length of light.

These experiments are a continuation of work commenced two years ago in which I was aided by a grant from the Elizabeth Thomson Science Fund.

EAST HAMPTON, LONG ISLAND,
September 28, 1911.

NO. 8.

SELECTIVE ABSORPTION OF LIGHT ON THE MOON'S
SURFACE AND LUNAR PETROGRAPHY.

In a preliminary communication entitled "The Moon in Ultra-violet Light" (Monthly Notices R.A.S., 70, 226, 1910, and Popular Astronomy, 18, 67, 1910) I showed that by photographing the moon with light of the shortest wave-length which is capable of traversing the earth's atmosphere, certain features are brought out which cannot be seen or photographed with visible light. The most conspicuous feature was the black area in the vicinity of the crater *Aristarchus*.

In the present paper I shall show that by combining photographs taken by light from three or more regions of the spectrum it may be possible to commence a study of the petrography of the moon's surface. The first experiments were made at my laboratory at East Hampton, Long Island, in the summer of 1909, with a home-made telescope with an objective of quartz, three inches in diameter, coated with a film of silver opaque to visible light, but transparent to the ultra-violet in the wavelength range λ 3,160 to λ 3,260. The telescope tube was mounted on an equatorial mounting improvised from the frame of an old bicycle and provided with slow motion for following in right ascension. Photographs made with this very clumsy outfit showed the dark spot bordering *Aristarchus*, and in the following autumn some better ones were made with a six-inch speculum of about ten feet focus.

In the following year two papers were published by Miethe and Seegert (Astron. Nachrichten, Nos. 4489, 4502, Band 188), who, however, worked with a screen of nitroso-dimethyl-aniline (the use of which as a filter for ultra-violet I published some ten years ago) and a silvered glass reflector, and consequently did not utilize the

region of the ultra-violet which is not transmitted by glass. They secured pairs of pictures made through an orange ray-filter and the nitroso screen, and by projecting them superposed and in register on a screen through a blue and a red-orange ray-filter obtained a two-color picture which brought out the local differences in the reflecting power of the moon's surface for the two spectrum ranges in question.

Last summer I took up the work again at East Hampton, setting up a 12-inch equatorial of speculum metal, and ordering a 26-foot glass reflector of 16 inches aperture from John E. Mellish of Cottage Grove, Wis. In the previous paper I have described the method by which a deposit of nickel was formed on this mirror, for it must be remembered that silver reflects only 4 per cent. of the ultra-violet light employed in the work, and is consequently no better than glass. This mirror I mounted in combination with a 16-inch cœlostat mirror, also nickelized. The arrangements for following were inadequate, however, and the photographs did not show much more detail than the smaller ones made with the six-inch mirror.

In the late autumn, through the courtesy of the Astronomical Department of Princeton University, I was given an opportunity of mounting the mirror on the 23-inch equatorial. I am under great obligation to Professor Russell for the interest which he took in the work and to Mr. Shapley, fellow in astronomy, who assisted me in handling the telescope and making the exposures. The 16-inch mirror was mounted at the eye end of the telescope and the plate-holder back of the objective, at the edge of the incident beam of rays. The use of the mirror in the Herschelian form of course impairs the definition somewhat with the ratio of focus to aperture which was used. Having had little experience with telescope mirrors, I was of the opinion, when putting the apparatus together, that the definition would be sufficiently good with this arrangement for the mirror in question, and as I was anxious to utilize as much of the light as possible, I adopted it.

The plate-holder was mounted on an old microscope stand

turned into a horizontal position, the rack and pinion serving for focusing. Three different regions of the spectrum were utilized. A deep-orange screen used in connection with a Cramer Iso plate furnished the yellow image, which represents pretty closely what we see in visual work. A very short exposure made without any screen gives us what I have designated as the violet image, and a screen made by silvering a sheet of uviol glass 1 mm. in thickness, made by Zeiss, gives us the ultra-violet image. This glass, in thin sheets, exercises no appreciable absorption for the range of wave-lengths transmitted by silver, and answers the purpose quite as well as quartz, which was used in the preliminary work. Careful experiments were made at East Hampton during the summer on the best thickness of silver film. If the film is too thin, much blue and violet light is transmitted, and the picture is made chiefly by these rays. If, on the other hand, it is too thick, nothing at all is transmitted, or the time of exposure is unduly prolonged. Photography of the spark through the screen is no criterion at all, for I found that a film which, with a short exposure, yielded only the group of iron lines in the region λ 3,160 to λ 3,260, when used for the ultra-violet photography of terrestrial objects illuminated by sunlight, gave pictures which could not be distinguished from ordinary photographs, *e. g.*, a glass jar containing cigars appeared transparent, showing the cigars distinctly. This circumstance is due to the fact that, owing to absorption by the earth's atmosphere, the intensity-curve is falling very rapidly in the ultra-violet. The best way to test a screen is to photograph the solar spectrum with a quartz spectrograph, and increase the thickness of the silver film until no trace of the blue, violet, and upper ultra-violet appears, the narrow band in the region specified alone appearing on the plate. Such a film barely shows the filament of a tungsten lamp, when eye observations are made in a dark room. If the filament appears at all bright the film is too thin. One film which I used failed to show the tungsten lamp at all, though this one was a little thicker than necessary. It is better to have them too thick

than too thin, for obvious reasons. The jar of cigars photographed through one of these films appears quite opaque, as if made of black glass.

The ray-filters were mounted immediately in front of the photographic plates. In some cases Iso plates were used for the violet and ultra-violet impressions, and in others Hammer Special and Lumière Sigma. It was found very difficult to guide satisfactorily with the large Princeton refractor, in spite of the fact that the large telescope was used for following. The motion in right ascension was especially troublesome, as it was accomplished by pulling a rope. Considering the large amount of motion in declination during the three-minute exposures, I am surprised that the pictures turned out as well as they did. An inspection of the three photographs, reproduced on Plate 9, shows that the reflecting power of different areas is quite different for the three spectral ranges utilized. The violet picture is the sharpest, as it was taken with an exposure of a second or less, and the lack of perfect definition is probably the result of the manner in which the plate was mounted, *i. e.*, off the axis. I have lettered certain regions on the ultra-violet picture which deserve special mention. The most conspicuous object is the large dark patch just above the crater *Aristarchus* marked *A*. Practically no trace of this appears in the yellow picture, while it is faintly visible in the violet one. Two enlargements of this region are reproduced, one from the yellow negative, the other from the ultra-violet. Other regions which are relatively dark in the ultra-violet picture will be found near the moon's limb above and to the right of *Aristarchus*, notably the maria *B* and *C*. On the other hand the maria *D*, *H*, and *G* come out relatively darker in the picture made with violet light. The mare *F* is lighter than *G* in the yellow and violet pictures, whereas in the ultra-violet picture they are of equal intensity.

The small crater indicated by the arrow at *E* and the two small craters to the right of it are equally bright in the yellow and

violet pictures, while in the ultra-violet, the crater *E* is much darker, almost disappears in fact.

It is very important in work of this kind to be sure that imperfections on the ray-filters or plates are not responsible for minute differences. A very slight variation in the thickness of the silver film will cause spurious effects, of course. I have verified the points mentioned on a number of negatives taken with the screens in different positions, which is the only way to distinguish between the real and the spurious.

It is obvious that the greater the number of widely isolated regions of the spectrum which we make use of in photographing the lunar surface the greater are the possibilities of drawing conclusions as to the nature of the materials of which the surface is composed. At the present time we can photograph only to wave-length $\lambda 8,000$ or thereabouts, but if we could extend the range say to 8μ , where anomalies in the reflecting power are shown by the silicates, we should probably find ourselves in the position to take up the subject of lunar petrography. Even with the range capable of investigation at the present time we can probably make a beginning, as I shall illustrate by a study of the *Aristarchus* dark spot, which, as I have said, is the most conspicuous object brought out by the ultra-violet photography. This spot is invisible in yellow light, begins to appear faintly in violet, and is very dark in ultra-violet.

I made a series of photographs with the three spectrum ranges used in the lunar work of a number of volcanic rocks. In this way I selected two specimens of volcanic tuff, of about the same color, one of which photographed dark in ultra-violet light. Superposing a small chip of this specimen on the other reproduced the conditions of the *Aristarchus* spot almost exactly. In yellow light the small chip was almost invisible against the larger, in violet it could be seen to be a trifle darker, and in ultra-violet it was very much darker than the background. I then analyzed the small chip and found that it contained iron and traces of sulphur. Photographs were now made of rocks

with surface stains due to iron, but the stains were equally dark in violet and ultra-violet light. I then formed a very thin deposit of sulphur in a spot at the center of a fragment of that specimen of the tuff which photographed light in ultra-violet. The deposit was absolutely invisible to the eye, and was formed by blowing a small jet of sulphur vapor against the surface for a second or two. I photographed the specimen with the three types of radiation, and found that the spot was invisible in the yellow picture, gray in the violet one, and quite black in the ultra-violet. The three pictures are reproduced. The large area and the general form of the *Aristarchus* spot suggested to me, when it was first discovered, that it was made of some material thrown out by a volcanic blast from the crater. It may be an ash containing sulphur or it may be a deposit of sulphur formed by condensation of ejected vapor. It seems probable, however, that it is due to sulphur. Zinc oxide I have found to be quite black in ultra-violet but it is quite as light in violet light as in yellow; therefore the spot cannot be zinc oxide, which would be less probable than sulphur, aside from the evidence cited. It is apparent that the introduction of the violet pictures has improved the method of analysis, and a further increase is desirable. By means of the infra-red screens, with which I have obtained most remarkable photographs of sunlit foliage showing snow-white against a sky as black as midnight, we can make photographs of the moon in the spectrum range λ 7,000 to λ 7,400, while the nitroso screen will give us pictures in the upper ultra-violet. With a series of five pictures made with five ranges of the spectrum between wave-lengths λ 7,400 and λ 3,160, it is probable that new facts would come to light, especially if the lunar pictures were made on a larger scale with an instrument capable of accurate following.

Light within the spectrum range λ 7,000 to λ 7,400 is but very slightly scattered by the earth's atmosphere, which accounts for the intense blackness of the sky in photographs made by light of this wave-length, and it does not seem impossible that photo-

graphs of the brighter planets made through an infra-red screen might prove interesting if the planets are surrounded by a light-scattering atmosphere, for we must bear in mind that the surface of the earth, as seen from a neighboring planet, would be seen through a luminous haze, equal in brilliance to the blue sky on a clear day, that is, it would present much the same appearance as is presented by the moon when seen at noonday.

A solution of cyanine and a yellow dye mixed together in such proportion that only the range λ 7,000 to λ 7,400 is transmitted makes an even better screen than the one which I used originally as has been observed by Pfund.

The plates obtained through the ray-filters can be studied to advantage by the methods employed in the three-color process of color-photography. Mr. F. E. Ives, the pioneer in work of this kind, was good enough to make at my request a three-color lantern slide from the three negatives. The negative taken through the ultra-violet screen was printed on a gelatin film and stained blue, the violet and orange pictures being rendered in red and yellow respectively. The three films when superposed resulted in a very pretty color photograph which brought out the differences in the reflecting power of the different maria in a very striking manner. The prevailing tone of the darker portions of the lunar surface was olive green but certain spots came out with an orange tone and others with a decided purple color. The dark spot near *Aristarchus* came out deep blue, as was to be expected.

I have applied this same process to the two photographs of the *Orion* nebula taken by Professor Hartmann and published in the Astrophysical Journal some years ago. One of these was taken through the nitroso-dimethyl-aniline screen which I described in the Astrophysical Journal for 1903, and the other through a screen which excluded the ultra-violet light. The marked localization of the two gases which make up the nebula is brought out most beautifully in the resulting color-picture. It is my plan next summer to begin work on photographing stars through the silver

ray-filter, for it seems probable that high-temperature stars will come out relatively very bright when photographed with the shortest wave-lengths.

Great care is necessary in the preparation of the silver ray-filter. I find that the uviol glass must be handled very carefully in the acid and alkali cleaning solutions. One of my plates, after having been cleaned a number of times, refused to take a uniform deposit, the silver coming down in streaks and cloudy patches, some parts of the surface refusing to take any deposit at all. More vigorous cleaning only made matters worse, and I found on washing and drying the plate that the surface had become badly corroded, resembling very old window glass which has been exposed to the weather. Repolishing with rouge is the only thing to do when this trouble appears. The silver film must be of uniform thickness, free from even the minutest pin-hole, and appear structureless by transmitted light. This last matter can be best examined into by placing a sheet of velox paper in a plate holder, covering the holder with the silver filter, and exposing for a few seconds to the light of the blue sky through an *open* window. The window should be at some distance in order that patches of irregular thickness, if they exist, may throw sharp shadows. On developing the paper any bad spots in the film become at once apparent.

As silver films of sufficient uniformity to serve as ray-filters require special precautions in their preparation a few words on this subject may not be out of place. The formaldehyde process gives the best results apparently, but it is very tricky to work with, and extremely sensitive to proportions, dilution, temperature, etc., acting in three or four wholly different manners according to circumstances. Commercial formaldehyde is diluted with ten parts of distilled water to form the reducing solution. Personally I never weigh my nitrate of silver as I enjoy the element of the personal equation, which enters the problem when scales are dispensed with. From one to two grams to 100 c.c. of distilled water are about right. Add am-

monia diluted with several volumes of water a little at a time until the precipitate is nearly but not quite dissolved. If too much is added and the solution clears add nitrate of silver solution, a drop at a time until a permanent straw tint is produced. The addition of the ammonia should form a good brown precipitate. Sometimes a very thin precipitate forms, the solution appearing pink or blue by transmitted light. I attribute this to too dilute nitrate solution, and find that it does not work as well as when the turbid brown precipitate forms. The plates carefully cleaned with nitric acid and caustic potash, and thoroughly washed with tap water, lifting them several times to get rid of the potash solution which lurks beneath them, are now flowed with a little of the reducing solution, just sufficient to wash over the surface when the dish is shaken. The dish is now tipped to one side and an equal amount of the silver solution is added, taking care not to pour it onto the plate but to one side. If the plate fills the dish it is better to mix the solutions in a beaker and then flow them over the plate. If the proportions and temperature are right the solution will turn pink in half a minute or so, the color deepening rapidly, and a beautifully uniform blue film will deposit. The process can be repeated until the film has the required thickness. I usually mount a tungsten lamp on the floor so that I can watch it through the bottom of the dish. Unfortunately things as described above seldom happen at the first trial. The silver may come down almost immediately, in brilliant streaks and splotches, the solution remaining clear. This means that too much of the silvering solution has been added. Or things may commence all right but the deposit may be brown like lightly smoked glass; the solution changing from pink to gray with a distinct precipitate. These brown deposits I find are non-conducting and are probably made up of very small particles. They have a low reflecting power. The trouble in this case is too little silver solution for the amount of reducing solution used. Sometimes the solution becomes muddy at once forming a brown deposit. I suspect that this results from too

dilute formaldehyde solution. It troubled me much when my personal equation contained one more variable than at present, but I have not seen it occur recently. As the production of the uniform blue film depends upon getting the proportions just right I suppose the beginner had best mix measured amounts for each trial, unless he has access to a large jar of silver nitrate which "belongs to the department." It is impossible to form a film of sufficient thickness with one silvering by this process. I usually pour off about half of the solution when the operation appears to be over and add a little more of the silvering solution. This usually doubles the thickness. For a second silvering mix the solutions quickly in a clean dish, using a little more of the silvering solution in proportion to the formaldehyde than for the first coating. Transfer the plate to this without washing. If it is washed, the silver is apt to frill in the second bath. The cause of this I do not know. Probably it is osmotic or perhaps catalytic(!).

I feel quite certain that the method of studying the lunar surface outlined in this paper is worth going on with, but only with the largest instruments, perfectly mounted, and under the best atmospheric conditions. The exposure factors for the screens should be carefully determined in advance by photographing well-lighted white paper through them (strip exposure by drawing slide out by degrees) and developing the plates simultaneously. The work can be done to advantage only by one who has had much experience with photographic plates, for it is no easy matter to get three images of the moon through the three specified screens all of which are properly timed and developed to exactly the same density. Unless this is done, very erroneous conclusions will be drawn, and I am not at all sure that my own pictures are wholly free from such defects.

Though a nickel-plated reflector is necessary if the silver ray-filter is to be used, I believe that results of interest can be obtained with an ordinary silver-on-glass reflector, using a nitroso screen in place of the silver film. This gives us an ultra-violet picture made with slightly longer waves than the ones which traverse

silver, but I have found that the spot near *Aristarchus* shows well with one of these screens.

I shall be glad to lend my thin plates of uviol glass to any observatory at which it is planned to take up the work with a nickeled reflector. The plates are 12 cm. square and 1 mm. in thickness, and I shall be glad to silver them anew with films of the most suitable thickness.

I have been aided in this investigation by a grant from the Elizabeth Thompson fund, made several years ago, and this communication is the final report.

NO. 9.

PRELIMINARY NOTE ON THE ELECTRON ATMOSPHERES OF METALS.

There has been a good deal of controversy recently as to whether air at atmospheric pressure will carry a current of electricity, when the potential between the electrodes is less than what is known as the critical potential (something over 300 volts). Earhart, in a paper published in 1901 (Phil. Mag. [6], i, p. 147), described experiments which appeared to show that a discharge might occur with as low a potential as 32 volts, the gap between the electrodes being of the order of magnitude of the wave-length of light. This result was called into question by Almy, who worked with very small platinum beads as electrodes, and failed to obtain any evidence of discharge at voltages below 300. During the progress of the work about to be described a paper appeared in the Phil. Mag. by Anderson and Morrison (May, 1912) which gives further evidence that currents may flow across minute air-gaps at very low voltages, though no data are given as to the precautions taken to exclude the presence of foreign matter between the plates, or how the exact distance between them was determined.

The experiments which I am about to describe were the out-growth of a piece of work on the electrical properties of very long heat-waves (112μ obtained by focal isolation) which has occupied a portion of my time during the past winter. Having found that quartz plates thickly coated with very fine copper dust, or with closely packed droplets of mercury, were perfectly transparent to the heat-waves, opacity commencing only when the size of the metal particles exceeded one quarter of the wavelength, I commenced experiments with silver films deposited on quartz and ruled with a diamond point into a microscopic

checker-board. The rulings were made for me by Dr. J. A. Anderson, who has worked out the technique of ruling thin metal films to such a point that clean cuts, quite through the metal, of a width certainly no greater and probably less than the wave-length of ultra-violet light are possible. The great trouble in making very close rulings on thin metal films is the tearing of the metal, which causes the cuts to run together. Successful rulings occur only when a natural edge of the diamond is used and the edge set accurately parallel to the direction of the cut. The silver was deposited on thin plates of quartz, the thickness being what is usually described as "half-silvered," and the plates were found to be absolutely opaque to the heat-waves. A cross ruling was then made breaking the film up into squares measuring about 0.1 of a wave-length on a side, *i. e.*, 0.011 mm. From the results of the experiments with the mercury droplets I expected to find the waves freely transmitted, but the ruled film was found to be quite as opaque as before. The electrical resistance of the film was then compared with that of an unruled one with a box-bridge and galvanometer, and found to be practically the same. This result seemed most astonishing, for the cuts when examined with a 1/12 inch oil-immersion objective were found to be clear through the film, there being no conducting bridge across the gaps.

A second film was now deposited on a glass plate, and wiped off with the exception of a strip about 3 mm. in width, terminating at each end in a larger patch of silver, against which the electrodes of silver-leaf rolled into soft balls were clamped. About 20 diamond cuts were made across the narrow strip, and its resistance measured. Before the cuts were made the resistance was 10 ohms, which was increased to only 13 ohms by the cuts. I feel confident that the diamond removed all of the metal from the cuts, for they appeared as brilliantly illuminated under the microscope as the clear glass from which all of the silver had been removed.

Photographs of the rulings were made with a 1/12 inch oil-

immersion objective, and the width of the cut determined by comparing it with the distance between the cuts, the measurements being made with a dividing engine. In the majority of cases the width turned out to be no greater than the diffraction maximum yielded by the objective, and in some cases it was probably less, the cuts appearing slightly grayish, as would be the case if the width was less than the resolving power of the objective. This makes the order of magnitude about equal to the wave-length of ultra-violet light, say 0.0003 mm. Photographs of the rulings are shown on Plate 7, Fig. 8.

A number of strips of silver were prepared, each one cut across by 20 strokes of the diamond, and the resistances measured by applying soft pads of silver-leaf as electrodes so as to include, or not include, the cross-ruled portion. The increase in the resistance was found to be very variable, for in some cases the original resistance of about 10 ohms was raised to three or four hundred, and in others to 15 or less. With cuts somewhat wider, say two wave-lengths, no trace of conduction could be found, and it seems probable that the great variation can be safely attributed to slight differences in the widths of the cuts, the differences being too small to be shown by the microscope. The voltage applied was that of one dry cell, and by means of a potentiometer it was found that conduction occurred with potentials as low as 0.001 of a volt. Covering the ruled portion with a drop of oil did not alter the resistance, though this is a point that has not been very thoroughly investigated.

It appeared to me possible that the conductivity at these very low voltages might be ascribed to the extent of the opposed surfaces. In all previous work the electrodes have been either spherical or "point and plane," and when brought close together gave us what amounts to two opposed points, on account of minute irregularities on the surfaces. If this explanation is the true one conductivity at greater distances should be obtained in the case of two opposed planes.

It is obviously out of the question to use metal plates as

ordinarily prepared for electrical experiments, and, as I shall show presently, even gold films deposited on optical flats by cathode discharge are scarcely suitable on account of minute conducting projections. Soft metals cannot be used, for if they are brought in contact there is the possibility of microscopic elevations being raised when they are separated. I accordingly commenced observations with the small optical flats of polished speculum metal, which is glass hard. The surfaces were known to be true planes to within $1/20$ of a wave-length, and they were highly polished and free from scratches. Two of these flats were placed in contact, no pressure being applied, and it was found that, so far as ordinary measurements would show, they were in metallic contact. The upper plate slid about easily over the lower with little friction, showing that they were separated by an air-film, and from what we know about the behavior of true flats brought together under these conditions, we may be certain that the actual distance between them is certainly 8 or 10 wave-lengths. Optical tests showed that the plates rounded off a trifle at the edge, the surface of the outer zone being a trifle convex, which excludes the possibility of true metallic contact occurring at some point at the edge. The speculum plates were now separated by two very fine quartz fibers, about 5 wave-lengths in diameter, as measured with the microscope, and again conductivity was observed, a current of several milliamperes being observed with an applied potential of one volt. The current increased rapidly and very steadily with the application of pressure, returning to exactly its original value as the pressure was removed. Fine sulphur dust was then allowed to settle from an air suspension upon one of the plates and the other plate then laid carefully upon it. Again conduction was observed. Metallic contact at any point was out of the question in this case. There was, however, the possibility that a conducting sulphide was formed, and consequently finely powdered quartz was substituted which gave similar results.

It was impossible, however, to measure the exact distance

between the plates under these circumstances, or be quite sure that the presence of the material used to keep the plates at a fixed distance was without influence. Fused quartz is known to be one of the best insulators which we have, and yet a film of adsorbed moisture might be responsible for the conductivity under the conditions of the experiment. I find it difficult to believe, however, that currents of the magnitude obtained, in some cases amounting to a considerable fraction of an ampere, can be carried in this way.

The ideal method is to exclude all material, and work under conditions which enable the exact distance between the plates to be determined. I accordingly used as opposed electrodes the half-silvered films of a Fabry and Perot interferometer. These can be adjusted to absolute parallelism by optical methods, and the exact distance between the metallic surfaces can be determined by placing a white light behind them and counting the number of interference bands which appear in the spectrum of the transmitted light between two lines of known wave-length. The interferometer plates were half-silvered by the formaldehyde process, which gives the most uniform semitransparent films, and were adjusted to parallelism with the soda flame, circular fringes appearing by transmitted light, the diameter of the central circle remaining fixed as the eye is moved about. The plates were mounted in the instrument a little to one side of one another, so that the silver-leaf electrodes could be brought into light contact with the silver films. One dry cell was used with a milliammeter and the plates were gradually approached. In every case a sudden large deflection of the milliammeter showed that metallic contact had occurred when the plates were still separated by a distance amounting to thirty or forty wave-lengths. It is apparently impossible to obtain silver films free from projecting metallic points, which bridge over the gap which separates them. I imagine that minute matter in suspension or particles of reduced silver settle on the film, and are not removed by the washing process. It seemed, however, as if a cathode

deposit of gold thrown down in a vacuum would be free from these objections. Semitransparent films of gold of beautiful quality were deposited on the interferometer plates and the experiment repeated. The same thing happened as before. After repeated trials, using great precautions to remove all dust particles from the glass surfaces, I finally obtained a pair of films which gave a small deflection of the milliammeter when separated by a distance of 28 wave-lengths. The fringes were still circular, or rather the entire surface of the interferometer plate appeared uniformly illuminated. On gradually approaching the plates the current increased with beautiful regularity, but when the plates were still over 15 wave-lengths apart a large deflection was suddenly obtained showing that metallic contact had occurred. As the plates were still further approached the fringes straightened out and crowded into the field, showing that there was something between the plates which caused a departure from parallelism. I have made repeated trials with gilded plates, but on only two occasions have I succeeded in getting the true effect before metallic contact occurred at some point. It is impossible to polish the films without making them much worse than before. What is required is a semitransparent film with an optical surface equivalent to that of a speculum plate. It is possible that by using a plate of gold which has never been previously used as a cathode, a suitable film may be procured, for it seems possible that the surface may be rendered spongy by disintegration, resulting in the projection of microscopic particles of gold against the film.

Very good results were obtained by gilding the convex surface of a plano-convex quartz lens of six-foot focus. The central zone of the lens was protected from the deposit by a circular disk of metal 5 mm. in diameter. An electrode of silver-leaf was attached to the gold film at the edge of the lens, which was then laid carefully upon a flat of speculum metal. The center of the system of Newton's rings observed with white light was brought to the center of the ungilded circular patch by placing

a small weight at the proper point on the lens which gave it the requisite tilt. Even at the center of the system the interference color was very pale, showing that the air-film was several wave-lengths in thickness at the so-called point of contact. By applying pressure it was ascertained that the edge of the zone at which the gilded surface commenced was about 8 wave-lengths from the speculum surface when a first-order color appeared at the center. The pressure was now removed causing a still further separation, nevertheless a current easily measurable with the milliammeter was obtained with one dry cell. If the lens was tilted by shifting the weight, the gold surface was brought into closer proximity to the speculum surface on one side of the ring system, and the ammeter indicated an increase of conductivity. This experiment is very easily repeated, and appears to be free from objection, but unfortunately it is not well adapted to quantitative work on account of the variable distance due to the curvature of one of the electrodes.

At this stage of the work I left Baltimore, taking it up again at my East Hampton laboratory. Using a D'Arsonval galvanometer I have obtained currents with much greater separation of the plates. By shaking up lycopodium in a jar and allowing the spores suspended in the air to settle on a speculum plate, I have succeeded in obtaining a very satisfactory series of readings by squeezing the plates together with a micrometer screw, the spores being quite compressible. In spite of the fact that they are very resinous and probably good insulators we have the possibility of absorbed moisture.

Similar results were obtained when the speculum flats were separated with small flakes of very thin mica. The flakes were freshly split, their thickness determined with the spectroscope, and they were torn to pieces with ivory forceps to avoid the possibility of metallic contamination, which might result if scissors were used. In all cases I find evidences that metallic conduction commences with one volt of applied potential when the plates are between 20 and 30 wave-lengths apart, but this

distance can be accurately measured only when semitransparent metallic films are used, so that my results have not been very consistent.

I have worked with the speculum plates mounted in the interferometer, and though I have obtained conduction before the plates appeared to be in contact, it appears to me that the separation can be much greater when mica flakes are present than when the gap is quite free from all material. With clean mica flakes pressed between the plates I have obtained conduction when light is still freely transmitted through the crevasse. With the plates mounted in the interferometer, however, the crevasse transmits little or no light when conduction commences. The light is of a deep blue color, which is an interesting observation, as showing that a narrow crevasse refuses transmission to the long waves first. The color effect is doubtless the result of the circumstance that the light which gets through has suffered multiple reflections, though the same thing would doubtless be observed, though to a less degree, with a metal having no selective properties.

Upon the whole I feel disposed to believe that the experiments indicate that the effect is a real one, due possibly to the presence of an atmosphere of electrons in the immediate proximity of metallic surfaces. I realize, however, that it will be necessary to carry out to a successful conclusion the experiment with the semitransparent films before any definite conclusion can be reached; for there seems to be evidence that the presence of a solid dielectric such as mica or quartz dust increases the effect.

NO. 10.

THE SATELLITES OF THE MERCURY LINES.

There have been many discrepancies among the observations, made by different observers, of the structure of the mercury lines, and even at the present time, with all of the work which has been done with echelons and interference plates, it is difficult to say positively just what is the actual structure of the lines. This is due in part to the circumstance that, with the most powerful echelons, the distance between the successive orders is less than the width of the group of satellite lines under observation, and in part to the ghosts and false lines which many instruments show. An excellent summary, with charts of the observations made by different observers, will be found in a paper by Gale and Lemon in the Astrophysical Journal for Jan., 1910. The authors of this paper made a series of photographs of the mercury lines with a large Michelson grating, and though these photographs do not show as much fine structure as has been found by observers working with echelons, they are more convincing than any photographs which have been published, so far as I know.

Having recently installed at my East Hampton laboratory a plane grating outfit of 42 feet focal length, for the study of the iodine absorption spectrum, and as it appeared that this instrument was far more powerful than the one employed by Gale and Lemon, it seemed worth while to make a study of the structure of the lines as shown under the enormous resolving power of this instrument.

It was found feasible to photograph the blue mercury line (4359) in the fifth order spectrum, for which the resolving power is 375,000 or about that of a large echelon. The green line and the two yellow lines were photographed in the fourth order, for which the resolving power was 300,000. At this point in the

spectrum the grating separates lines only $\frac{1}{300}$ of the distance between the D lines apart. That the grating actually yielded its full theoretical resolving power was amply proved in the study of the absorption spectrum of iodine vapor.

A description of the grating and the method of mounting will be found in a previous paper (No. 2), and I need only state in the present paper that it was a very excellent plane grating ruled by Dr. Anderson on the 15,000 machine, ruled surface $3\frac{1}{2} \times 5$ inches (or 75,000 lines in all) mounted in the Littrow form behind a six-inch achromatic lens, kindly placed at my disposal by Professor Campbell of the Lick Observatory. The focal length of the instrument was double that of the one used by Gale and Lemon, and the resolving power of the grating was certainly three times as great as theirs, as will be seen from a comparison of the photographs which accompany this paper with theirs (Fig. 4 of Plate 10 in particular). —

The source of light was a Cooper-Hewitt mercury arc, used "end-on." The use of the tube in this position materially shortens the exposure, without giving rise to any reversal effects so far as I can see, though the relative intensities of some of the satellite lines appears to be a little different from that which obtains when the light is taken from the side of the tube. This is of course due to what we may term the first stage of reversal, certain satellite lines being weakened by absorption more than others, the phenomenon being analogous to one which I mentioned some years ago, namely that a hydrogen tube appears red when viewed from the side, and bluish white when seen end-on (Phys. Zeitschrift, 1906, page 926). The time of exposure varied from 30 minutes to an hour, which compares favorably with the time required with large echelons.

The last paper on the structure of the mercury lines which I have been able to find is that of Lunelund (Annalen der Physik, 34, page 505, 1911) and as comparative tables of the observations made by all previous observers are given in this paper, I shall make no other references. From a comparison of these tables

with the photographs obtained with the grating one cannot but help feeling grave doubts about accepting the results yielded by the echelon or interference plate, until they have been checked up with a grating, except in special cases. This is especially so in the cases where the width of the group of satellite lines is greater than the distance between the spectra of adjacent orders, which is often the case.

It is customary to give the positions of the satellite lines to the right and left of what is called the main line, in terms of + and - fractions of an Ångström Unit. Some ambiguity results from this, owing to the circumstance that different observers do not always choose the same point for the main line, as for instance in cases where the main line is a doublet, an observer working with an instrument incapable of resolving it would choose its center of gravity as his zero point while an observer who resolved the line would choose the stronger component. An example of this will be found in the case of my results on the 4359 line.

My own study of the lines were made at the end of the summer, just before closing up my laboratory, with a view of determining whether any new data of value could be obtained. At the time I was unable to refer to any of the previous papers on the subject, and consequently was unable to make a further study of the discrepancies which were found as soon as comparisons were made. Next summer it is my plan to place the spectrograph in an underground tunnel, and secure a larger grating if possible, for the results obtained already indicate that but very little further improvement will make the instrument equal in resolving power that of the largest interference spectroscope, and at the same time furnish results about which there will be no ambiguity. We will now consider the results obtained in the case of the four lines which I have already investigated.

THE 5769 YELLOW LINE.

A photograph of this line made in the fourth order is reproduced on Plate 10, Fig. 1. I have indicated the middle of the

main line in each case with an ink dot. The positions of the satellites are as follows:

+ .042
0
Main line.
- .055
- .112

An inspection of the photograph is sufficient to convince us that all of these satellites are real, and yet the one to the left (.112) was missed by Gale and Lemon, as well as by all of the other observers except Lunelund, who gives it the same value (.112) and Janieki who placed it at .113. Nagaoka records a satellite at $- .109$, which may be identified with it, but his photographs indicate the presence of so many false lines and ghosts that it is difficult to be very sure of anything. I cannot understand why the Michelson grating failed to record it, though as I have already stated the use of the tube "end-on" intensifies many of the fainter companion lines. Lunelund's other values agree very well with those given above, though I find no trace whatever of the satellites, $+ .084$ and $+ .121$ which he regards as probably real. He gives their intensities as about one half that of the one at $- .112$, yet the most careful scrutiny of my photograph fails to reveal the slightest trace of it, though $- .112$ is fully four times as black as the minimum visible on a photographic plate. I feel therefore quite certain that these satellites are spurious.

THE 5790 YELLOW LINE.

This line is shown by Fig. 2, Plate 10, and the satellites are as follows:

+ .222
+ .164
+ .131
0
Main line.
- .124
- .191

and two lines at $- .944$ and $- 1.007$

About these last two there is absolutely no question. Gale and Lemon found them, and I have repeatedly seen them as a

single line very close to the main line with a low power spectrograph (plane grating and lens of one meter focus). I never regarded this companion line of the yellow line as a satellite, and was surprised to find it so close to the satellite group with the forty-two foot spectrograph. There is on the plate perhaps a faint suggestion of the satellite at $+.082$ but I should want to take another photograph with a longer exposure before being sure of it. No trace appears of the fainter components given by Lunelund, and I am surprised to find that he does not include the close pair well to the left of the group in his list of lines the existence of which is established, for the photograph published by Gale and Lemon established their reality beyond question.

THE 5461 GREEN LINE.

The spectrograph was not giving its best definition on the evening on which this photograph was taken, on account of a high wind, and the resolution is no better than in the one made by Gale and Lemon. I have only to record the discovery of a broad faint band on the short wave-length side of the satellite at $-.233$. The edges of the band are at $-.327$ and $-.414$. It is very distinct on the original plate, but has lost much in the process of enlargement, and as it may vanish entirely in the reproduction I have retouched it in the upper half of the picture, Plate 10 (Fig. 3). No trace of this has been found by any previous observer, but there is no doubt about its existence.

THE 4359 VIOLET LINE.

This line was photographed in both the fourth and fifth orders: The fourth order showed the middle line double, a sharp narrow line to the left, and a broad one to the right. The fifth order divided the broad component into two, the middle line being resolved into a triplet. I believe that it is still more complex. This photograph is reproduced on Plate 10, Fig. 4, print *a* being made darker than *b* to bring out the division of the middle line. The superior resolving power of the grating is well shown by

comparing this picture with the one made by Gale and Lemon. I suspect that some of their trouble arose from vibrations and striae due to air currents, for their photograph made in the fifth order does not appear to show any greater resolving power than the one made in the third. The positions of the satellites are as follows:

+ .212	Faint: not shown on print, and never observed previously.
+ .168	
+ .130	
+ .091	
+ .029	
0	Main line.
-.034	
-.111	} Barely resolved.
-.124	
-.174	
-.219	} Very faint and never observed previously .
-.282	

These values agree well with the ones found by Gale and Lemon, though we have not taken the main line at the same point, which results in a slight shift of the one set of readings with respect to the other. I consider the position of the main line which I have taken to be the correct one, for the middle line (triplet) is clearly resolved, and the central component is by far the brightest. Gale and Lemon evidently took the left-hand component, but there is scarcely any trace of resolution in their photograph.

The satellite + .168, which is the narrow bright one to the right in my photographs, was found by Von Baeyer (given as + .188) but was not found by Janicki, Galitzin or Lunelund, which is sufficient evidence that the interference spectrosopes are not very reliable.

The resolving power of the best ones is only a very little greater than that of the grating with which I have worked, and in my opinion they can only be used to advantage for a supplementary study of the groups of satellite lines after the chief features of the group have been ascertained with the grating.

It is my opinion that the four photographs reproduced with this paper furnish the most reliable information regarding the structure of these mercury lines which we have at the present time.

The placing of the large spectrograph in an underground tunnel will improve its performance, I am sure, as I always found some trouble from striae (schlieren) stirred up by air draughts down the long tube. It is my hope also that a somewhat larger grating may be available by that time.

NO. 11.

ON THE IMPRISONMENT OF RADIATION BY TOTAL
REFLECTION.

My attention was drawn recently to a somewhat surprising circumstance in connection with fluorescence by Dr. Cooper Hewitt. As is well known he has now perfected his rhodamine fluorescent reflectors for the mercury arc to such a point that the red fluorescent radiation, plus the direct light of the arc, makes a fairly good imitation of daylight. He found that if the celluloid film stained with rhodamine was backed by white paper the fluorescence was many times brighter than when a backing of silver paper was used. I verified the matter by depositing silver chemically over a small circular area in the center of a white porcelain plate, and flowing the whole with the rhodamine solution, or with water containing a little fluorescein. Notwithstanding the very high reflecting power of the polished silver film, the intensity of the fluorescence over the circular area was so feeble that it appeared almost black in contrast with the brilliant fluorescence displayed over the surface of the porcelain. The plate was illuminated with the mercury arc in the case of the rhodamine, or with that of the carbon arc, passed through dense cobalt glass in the case of the fluorescein, the experiment being well suited for lecture purposes. If we strip off the colored celluloid film from the porcelain plate we find its fluorescence becomes even less brilliant than that of the portion backed by silver. The action of the white porcelain surface in raising the intensity of the fluorescence of the film covering it appeared a little puzzling at first. It was noticed, however, that the films which had been stripped from the surface glowed brilliantly *along the edges*, and this circumstance gave me the clue to the action of the matt reflecting surface. The greater luminosity

of the edges was evidently due to the circumstance that more radiation was able to escape here than through an equal area of the surface of the film. The action of the matt surface will be clear from reference to Fig. 1, in which AB represents the upper,

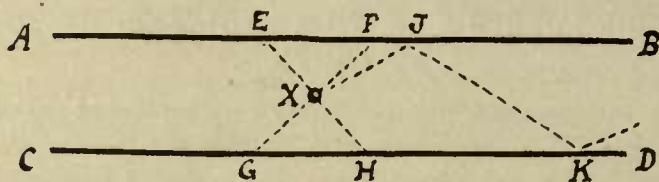


FIG. 1.

and CD the lower surface of a celluloid film stained with rhodamine. Let X represent a fluorescent molecule from which radiation of equal intensity escapes in all directions. Of all the rays leaving X it is clear that only those within the solid cones EXF and GXH can escape into the air. The rays within the cones FXH and EXG are imprisoned by total internal reflection, the ray XJ for example being reflected back and forth between the parallel surfaces of the film. Silvering the lower surface will cause the rays in the cone GXH to escape through the upper surface, but will not affect the paths of the other rays. If now we bring a white matt surface into optical contact with the lower surface of the film, it will liberate all of the rays which were totally reflected. Take the rays XJ for example; it is diffusely reflected at K , and that portion of the energy within a cone of the same aperture as that of the cone EXF escapes through the upper surface. The rest is totally reflected from the upper surface, and returned to the white surface, when the process is repeated, all of the energy, except that lost by absorption, eventually passing out through the upper surface. The action of the matt surface liberates the energy imprisoned by internal reflection. If there were no absorption the edges would appear of dazzling brilliancy, as all of the imprisoned energy would be thrown out here. The greater brilliancy of the edges of a fluorescent film was utilized

by Becquerel in observing the faint luminosity of certain compounds of uranium, and by Greinacher in the case of the fluorescence of mica films caused by radio-tellurium (Phys. Zeit., 1906).

We may test the above theory of the action of a matt surface in increasing the brilliancy of the fluorescence by making photometric measurements. The ratio of the energy within the two cones of rays which can escape without the aid of the matt surface, to the energy imprisoned by reflection, is represented by

$$\frac{1 - \cos \theta}{\cos \theta}$$

which is the ratio of the area on a sphere described around the luminous molecule, cut out by the cone of rays *EXF* to the area of the hemisphere minus this portion. For celluloid the critical angle is about 40° , *i. e.*, $\theta = 40^\circ$ and

$$\frac{1 - \cos \theta}{\cos \theta} = 0.31;$$

in other words, the imprisoned energy is about 3 times greater than the energy which escapes. Its liberation by the matt surface should therefore give us about fourfold increase in luminosity. This point was tested with the photometer. As a standard source a rhodamine screen (matt) illuminated by the light of the mercury arc was used, its light being passed through two nicol prisms by which its intensity could be varied by a known amount. It was compared with a rhodamine film in part covering white porcelain, and in part highly polished silver. The photometer used was a very simple but very satisfactory one made by Dr. Pfund, a semicircle of silvered glass taking the place of a Lummer-Brodhun prism. Equality of luminosity of the two fields of the instrument, with disappearance of the dividing line, was secured in the two cases with the nicols rotated 11° and 22° from the position of extinction. This means that the rhodamine film on porcelain is 3.8 times brighter than the

one on silver, which is in good agreement with the calculated value (4). In making the observations a red glass was placed in front of the photometer to exclude everything except the fluorescent light. (White porcelain alone, illuminated by the mercury arc, appeared practically black when viewed through the red glass.) On completing the work it occurred to me that the case was similar to the one to which I drew attention several years ago, namely that a fused bead of microcosmic salt, raised to the highest temperature possible with a blast lamp, emits little or no light when removed from the flame, though the platinum wire supporting it glows vividly. This is of course a fine case of the failure of a transparent body to radiate, which is what Kirchhoff's law demands. But as the bead cools down it solidifies and numerous cleavage planes appear. At the moment of crystallization it glows with a dull red light, which persists for several seconds. I found difficulty in explaining this (see *Phys. Optics*, 2d edition, page 598) but a suggestion made by Prof. C. E. Mendenhall certainly gives us a satisfactory hypothesis, though there still remain some points which are not quite clear to me. Professor Mendenhall considered that the action of the cleavage planes was merely that they interfered with the imprisonment of radiation by total reflection. All rays originating within the ball which strike the surface at an angle greater than the critical angle are reflected around the inner surface over and over again, so that they eventually may be considered as having traversed a layer of the medium of infinite thickness. If the medium has any absorption at all, and no media are perfectly transparent, this radiation will be of the same type as that of a black body at the same temperature. Scratches on the surface or internal cleavage planes liberate this energy by interfering with the total reflection.

Professor Mendenhall has suggested that I include some of his observations in the present paper.

He writes me that he made a scratch on the surface of a ball of fused quartz, which was then heated in a Bunsen burner. The

black body temperature of the scratch, as observed with an optical pyrometer, was 850° C., while that of the rest of the ball was barely 600° C.

From similar considerations he concludes that a uniformly heated, nearly transparent sphere should appear more luminous towards the limb. (A solid incandescent sphere appears as a uniformly illuminated disc, as a result of the cosine law.) I have verified this with a hollow glass bulb filled with a very dilute solution of rhodamine, illuminated by the mercury arc and viewed through red glass. If a spot on the surface of the bulb is finely ground with flour emery, this spot appears extremely luminous when near the limb, as a result of the liberation of the fluorescent rays which are undergoing total internal reflection. The bulb appears slightly more luminous at the limb, even when the surface is not roughened. I have observed the same thing in films of celluloid stained with rhodamine, which appear much more luminous when viewed obliquely, at nearly the angle of grazing emergence, than when observed by rays which leave the surface nearly parallel to the normal.

In the case of the fused bead of microcosmic salt it is probable that the increase in brilliancy which accompanies the formation of cleavage planes is due in part, if not wholly, to the reflection and refraction of the light emitted by the white hot supporting wire. I have not been able to devise any satisfactory way of getting rid of a luminous support, but I have dropped molten beads from the fifth floor of the laboratory and watched their descent down the five stories of the dark hallway at night. The glow appeared to decrease steadily with the descent, which indicated that there was no increase of luminosity. If the bead could be held stationary in a strong vertical current of air, the condition for observation would be more favorable.

DESCRIPTION OF PLATES 1 AND 2.

Spectra A and B. Resonance spectra of iodine excited by illuminating the vapor with the light of the Cooper-Hewitt mercury lamp. (All of the spectra with the exception of *A* are reproduced as negatives, as the fainter lines are brought out more clearly in this way.)

Spectrum C. Resonance spectrum excited by the light of the high temperature mercury arc in quartz tube.

Spectrum D. Resonance spectrum excited by the green mercury line, and *E* by the two yellow mercury lines.

Spectrum F. Small portion of the resonance spectrum between the green mercury line (to the left) and the two yellow lines (to the right) photographed with the concave grating. (Cooper-Hewitt lamp excitation.)

Spectrum G. Same as above but with excitation by the quartz mercury lamp. The two small inserts below this spectrum show the removal of one of the faint companion lines in each of the resonance groups, by filtering the exciting light through bromine vapor.

Spectra H, I, J. Transformation of the resonance spectrum into a band spectrum by helium.

Spectra K and L. Resonance groups highly magnified; *M* indicates the width (on the same scale) of the group of absorption lines of iodine which falls within the green mercury exciting line.

Spectra N. The green emission line of the quartz mercury lamp at different temperatures.

Spectrum O. The green emission line of the quartz mercury lamp after passage of the light through iodine vapor, showing the group of absorption lines responsible for the multiplex excitation. Below, and in coincidence with this is the green emission line of the mercury arc running at a low temperature.

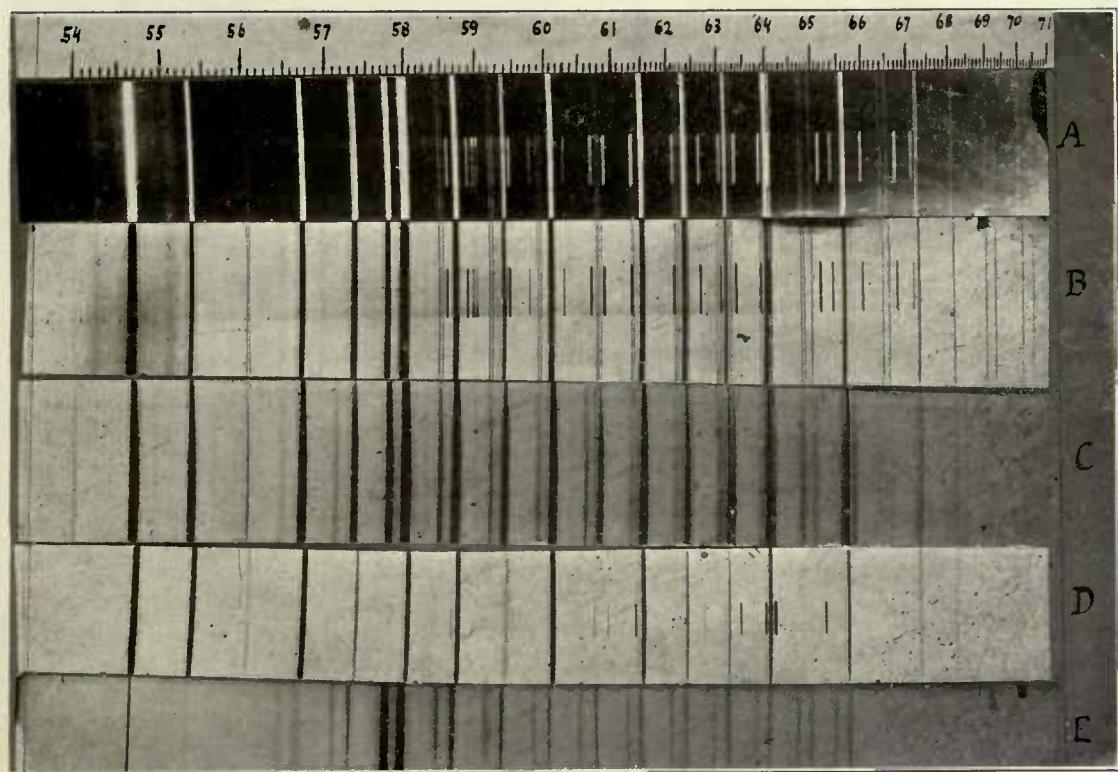


PLATE 1.

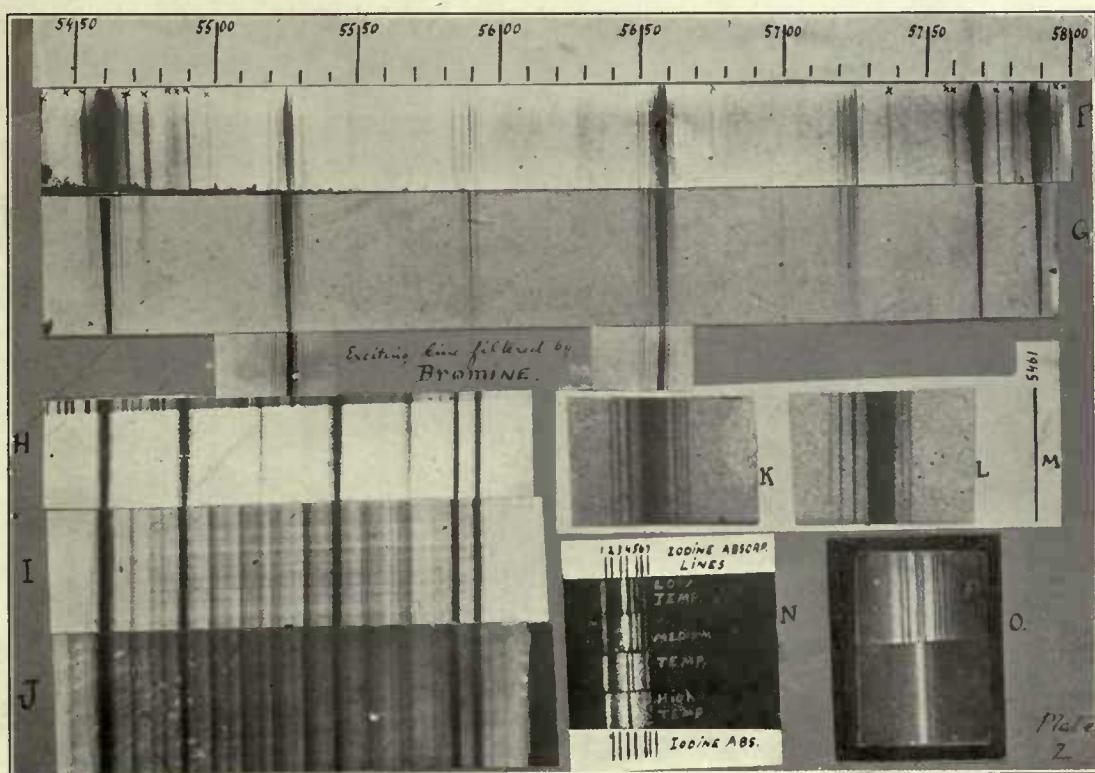


PLATE 2.

DESCRIPTION OF PLATE 2a.

Upper photograph. The fluorescent cone of light caused by focusing the light of the mercury arc at the center of a glass bulb, highly exhausted and containing a small crystal of iodine, which fills the bulb with iodine vapor at a very low pressure.

Lower photograph. Savart fringes cutting across the cone of fluorescent light, showing that the light is partially polarized.

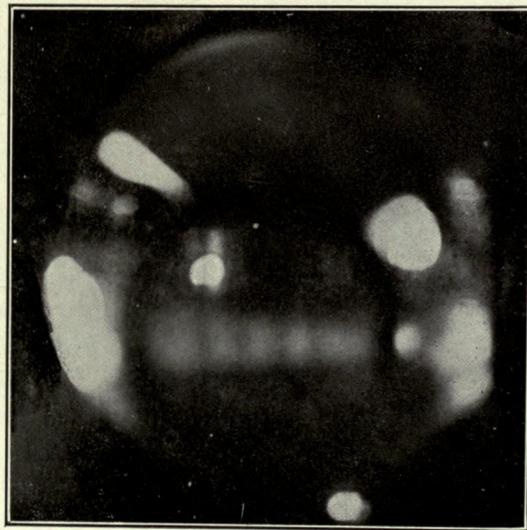
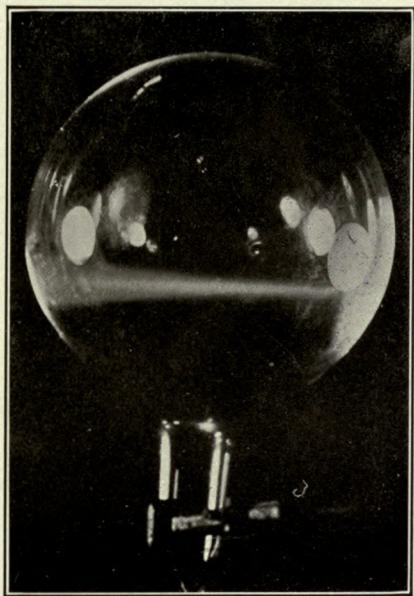


PLATE 2a.

DESCRIPTION OF PLATE 3.

Photographs made with the 40-foot spectrograph at East Hampton.

Spectrum P. The green line of the Cooper-Hewitt mercury arc (above) with its satellites, and the absorption lines of iodine in the same region of the spectrum (green line of the quartz mercury lamp below).

Spectrum Q. Above: The green mercury line of the quartz arc, with its center reversed. Below: Same line when the lamp is first started and running at a low temperature.

Spectrum R. Absorption of bromine (above) in coincidence with the absorption of iodine (below), the groups of lines falling within the green emission line of the quartz mercury arc.

Spectrum S. Above: The green mercury line, Cooper-Hewitt lamp (short exposure). Below: Iodine absorption lines in same line from quartz mercury lamp.

Spectrum T. Green line of quartz lamp above, iodine absorption lines in same line below.

Spectrum U. Same as *P*, but shorter exposure.

Spectrum V. Bromine absorption (above) in coincidence with iodine absorption below. Sunlight used. Width of region shown 8 Ångström units. The iodine lines which are covered by the green mercury line indicated by a ~.

Spectrum W. Iodine absorption photographed with the 40-foot spectrograph (below). Same region enlarged to same scale from Hasselberg's map. Hasselberg has placed the solar lines above.

Spectrum X. Absorption of sodium vapor and iodine within the region covered by the 5769 yellow mercury line of the quartz lamp. The iodine is the middle spectrum, sodium above and below.

Spectrum Y. The 5790 yellow mercury line with its components.

Spectrum Z. Above: The 5769 emission line of the Cooper-Hewitt lamp. Below: The absorption of iodine vapor within the same line emitted by the quartz lamp.

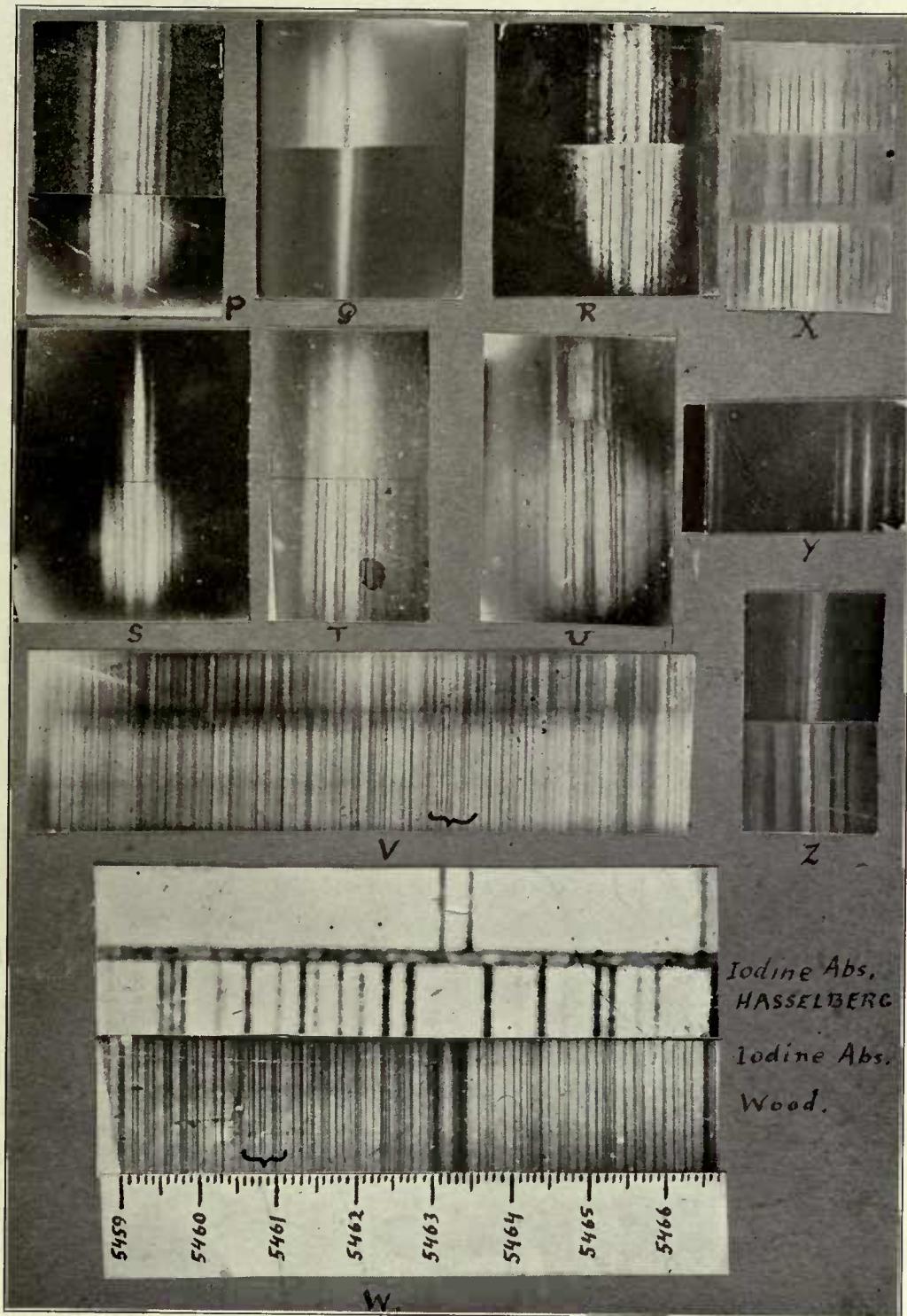


PLATE 3.

DESCRIPTION OF PLATE 4.

The 40-foot Plane Grating Spectrograph at East Hampton.

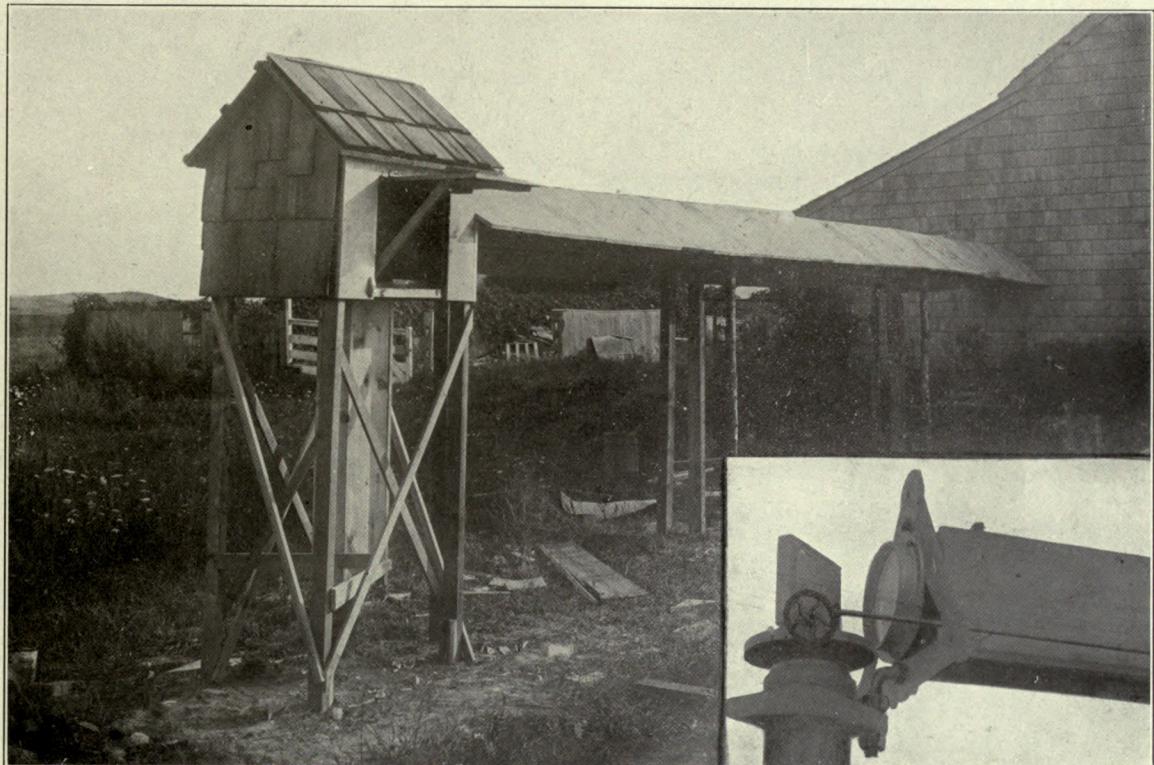


PLATE 4.

DESCRIPTION OF PLATE 5.

SELECTIVE SCATTERING, ABSORPTION AND REFLECTION OF LIGHT BY RESONATING GAS MOLECULES.

FIG. 1. Mercury vapor at room temperature scattering ultraviolet light by resonance. (Resonance radiation.)

FIG. 2. Spectrum of the light of a mercury lamp, and the spectrum of the light scattered by the cold mercury vapor (a single line only).

FIG. 3. Illustrating the strong absorption by a layer of mercury vapor at room temperature 8 mm. in thickness, of the light emitted by the cold mercury vapor.

FIG. 4. Illustrating primary and secondary resonance radiation.

FIGS. 5, 6 and 7. Illustrating the gradual transition from selective scattering to regular reflection by mercury vapor.

FIG. 8. Resonance radiation of mercury vapor in air at different pressures.

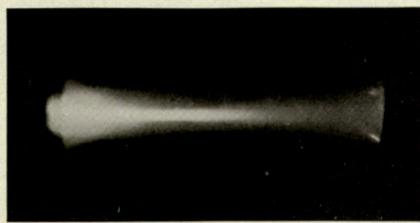


FIG. 1.

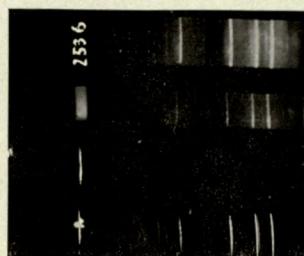


FIG. 2.



FIG. 3.

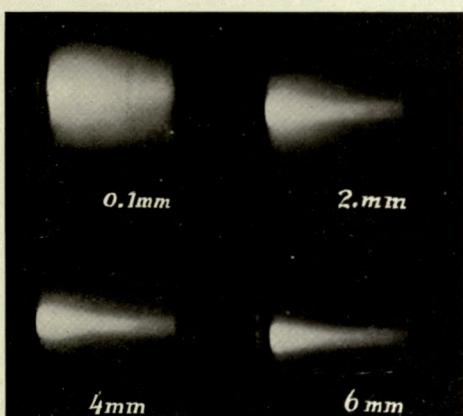


FIG. 4.

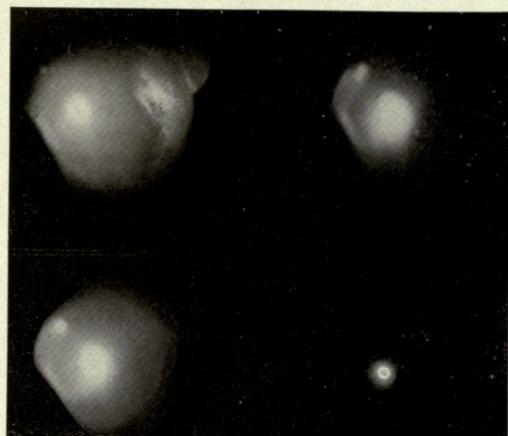


FIG. 5. Flask.

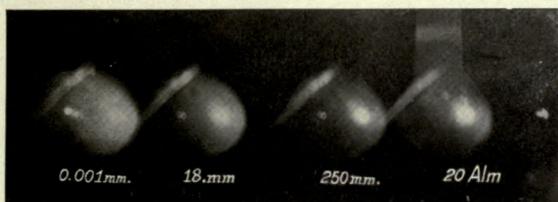


FIG. 6. Bulb.

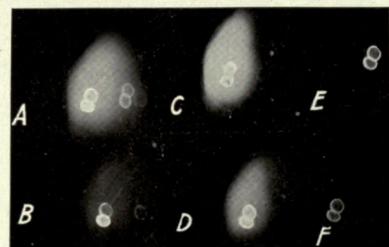


FIG. 7.

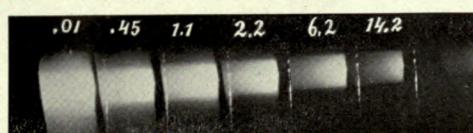


FIG. 8.

PLATE 5.

DESCRIPTION OF PLATE 6.

FIG. 9. Shadow of a small quartz bulb containing mercury vapor at room temperature thrown on a photographic plate by the light emitted by cold mercury vapor.

FIG. 10. The same with the mercury vapor removed.

FIG. 11. Column of mercury vapor rising from a drop of warm mercury photographed with the light of the resonance lamp.

FIGS. 12 and 13. Illustrating the study of the ratio of the scattered to the absorbed light.

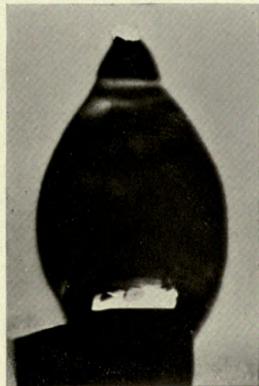


FIG. 9.

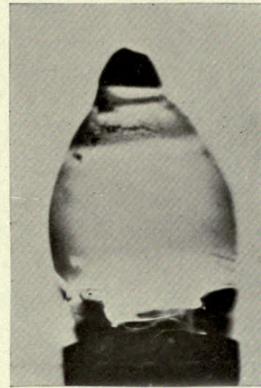


FIG. 10.

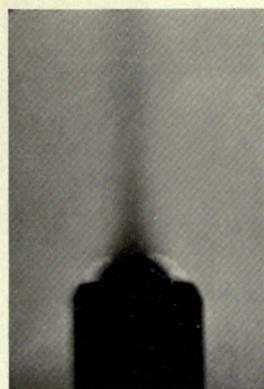


FIG. 11.

PLATE 6.



FIG. 12.

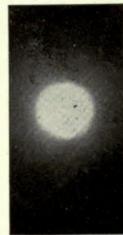


FIG. 13.

DESCRIPTION OF PLATE 7.

FIGS. 1 to 6. Micro-photographs of small portions of the resonator plates used in the experiments with the long heat waves. The resonators are droplets of mercury formed by condensing the vapor on a quartz plate. A scale graduated to 0.01 mm. is shown below, from which the diameters of the droplets can be calculated.

FIG. 7. The 2536 ultraviolet line of mercury in coincidence with the iron lines in the same region. Illustrating paper on the selective dispersion of mercury vapor.

FIG. 8. Rulings made with a diamond on a silver film deposited on quartz used in experiments with long heat waves. (Highly magnified.)

FIG. 9. Interferometer fringes in the ultraviolet region of the spectrum, illustrating paper on the dispersion of mercury vapor.

FIG. 10. Shift of the interference fringes in the vicinity of the 2536 absorption line of mercury, caused by the introduction of mercury vapor in one of the optical paths of the instrument.

FIG. 1.

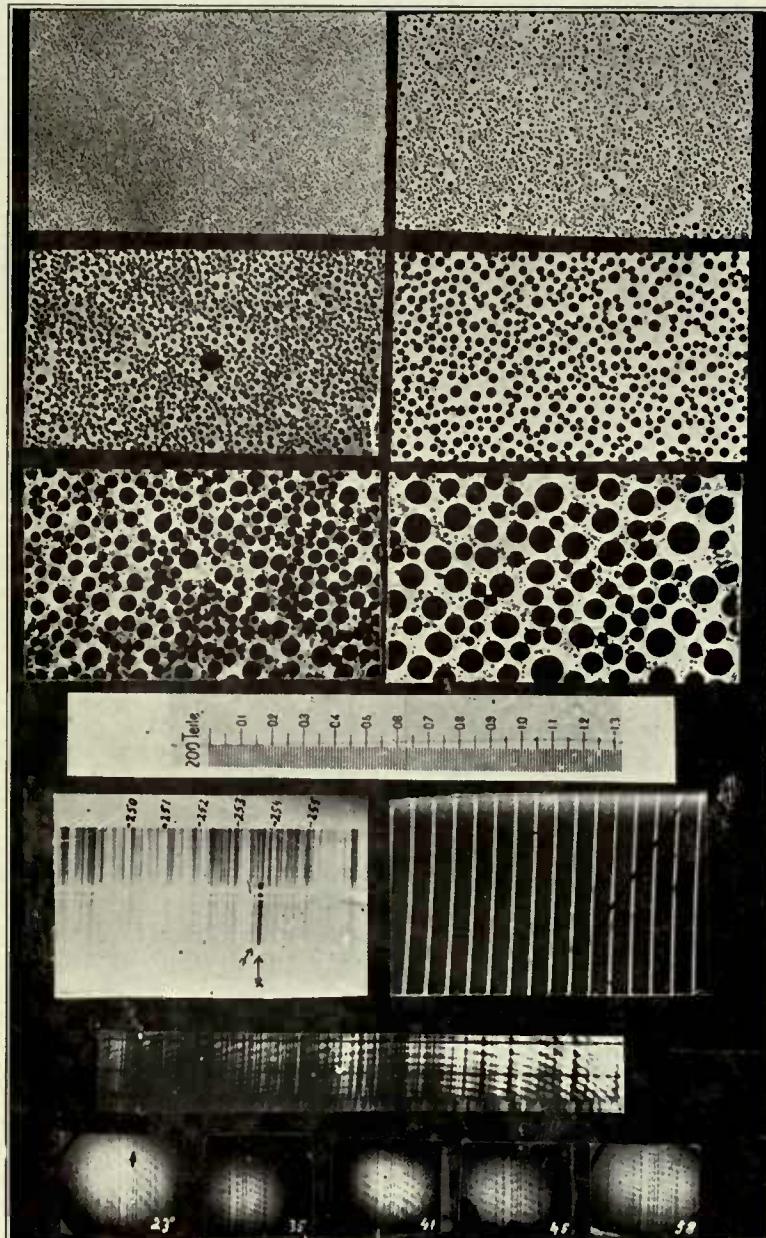


FIG. 2

FIG. 4

FIG. 6.

FIG. 8.

FIG. 9

FIG. 10

PLATE 7.

DESCRIPTION OF PLATE 8.

ILLUSTRATING PAPER ON NICKELED GLASS REFLECTORS.

FIG. 1. The spectrum of the cadmium-tin spark reflected from a film of nickel and from a film of silver, showing the failure of silver to reflect at wave-length 317.

FIG. 2. The spectra of the light of the iron spark reflected from silver and from nickel, and transmitted through a thin film of silver.

FIG. 3. Illustrating the reflecting power of glass, silver, nickel and speculum metal for light in different regions of the spectrum.

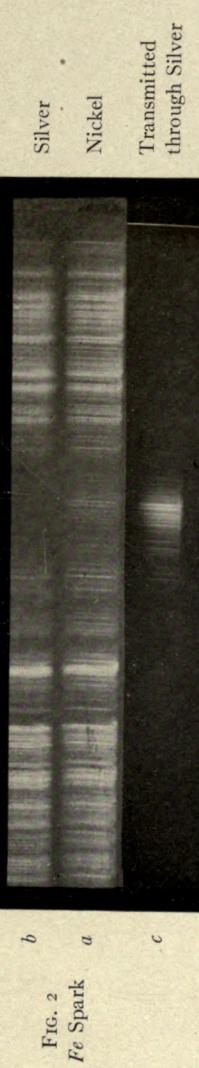
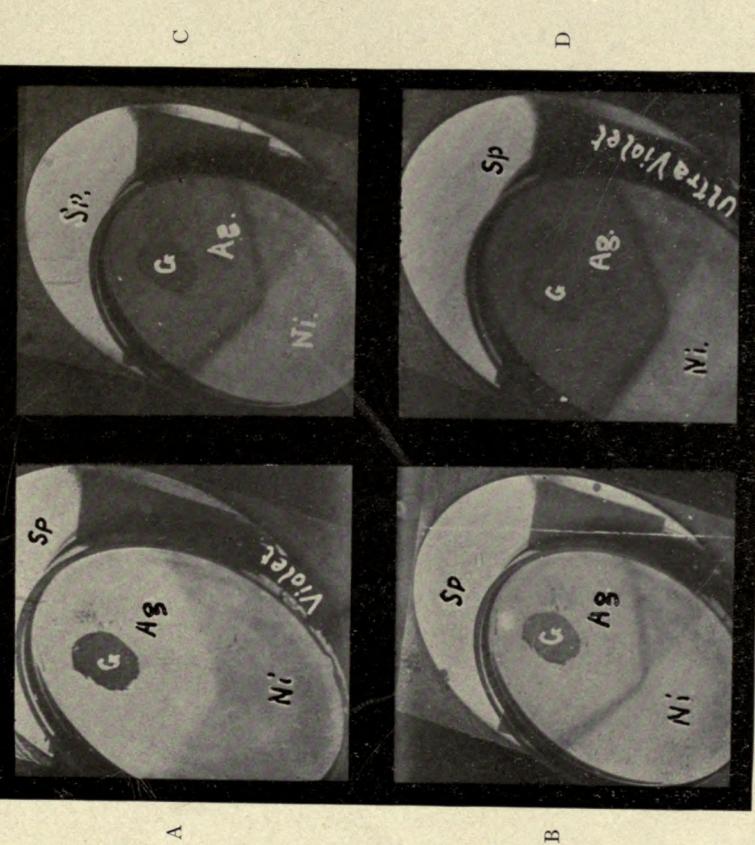
Transmitted
through Silver

FIG. 3

DESCRIPTION OF PLATE 9.

ILLUSTRATING PAPER ON THE SELECTIVE REFLECTION OF LIGHT FROM THE
MOON'S SURFACE.

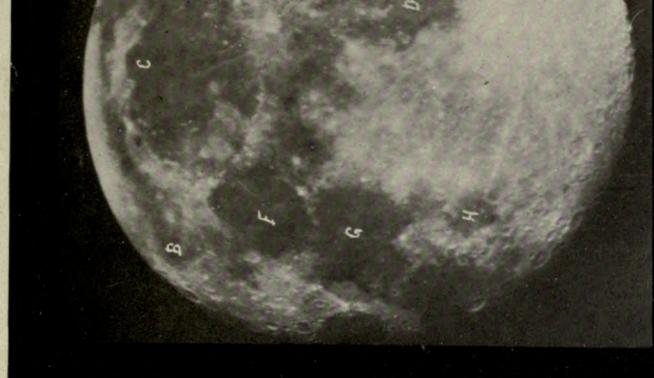
Three views of the entire moon taken by yellow, violet and ultraviolet light.

Two enlargements of the region around the crater Aristarchus (indicated by an arrow) showing the black deposit which appears in the photograph made by ultraviolet light. (Probably sulphur.)

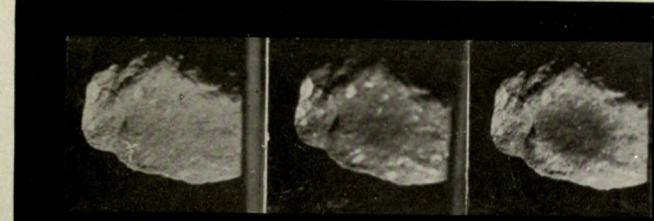
Three small photographs of a very light deposit of sulphur on a fragment of ochre-colored rock taken by yellow, violet and ultraviolet light.



Yellow



Ultra-Violet



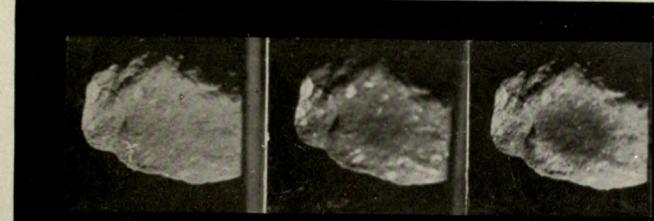
Violet



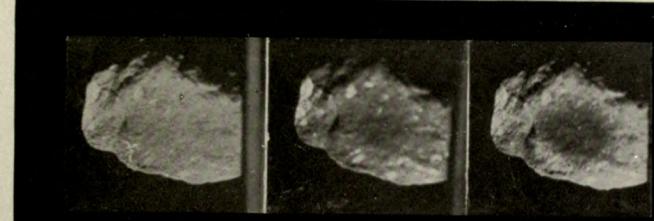
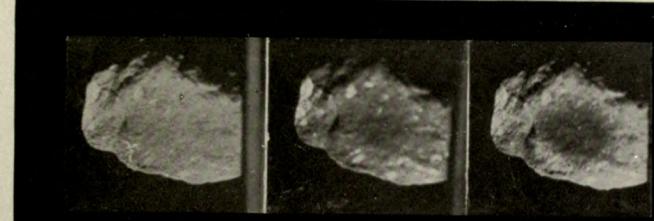
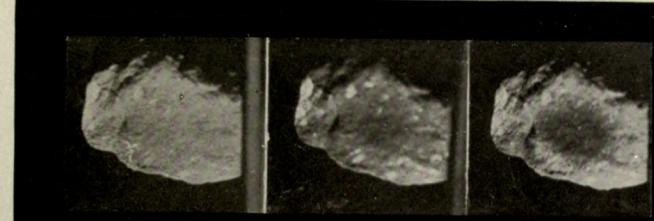
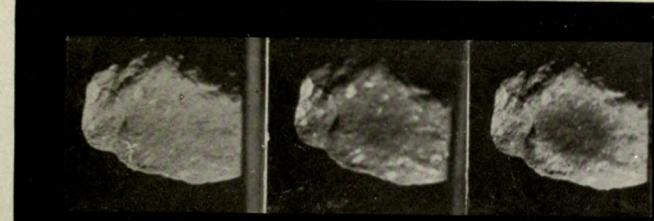
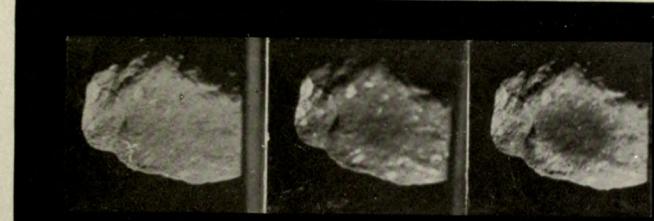
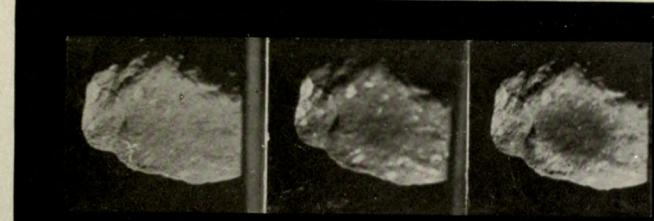
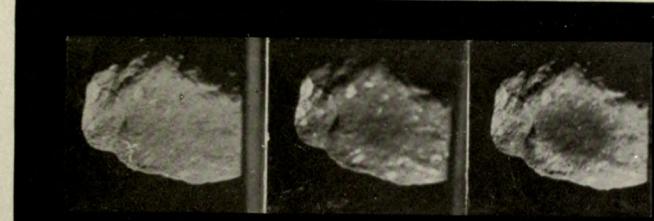
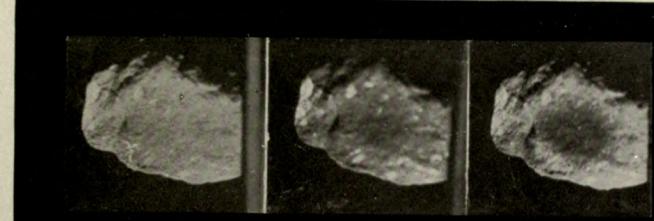
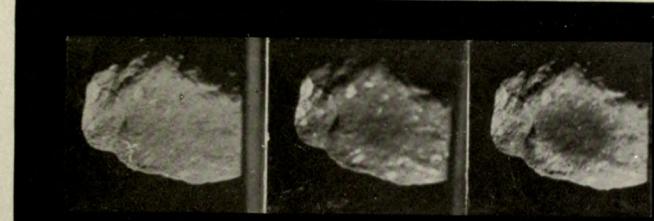
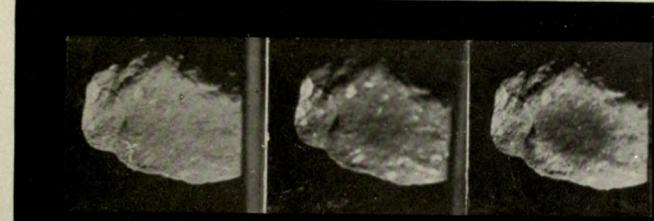
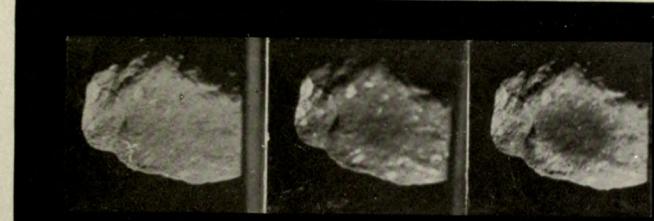
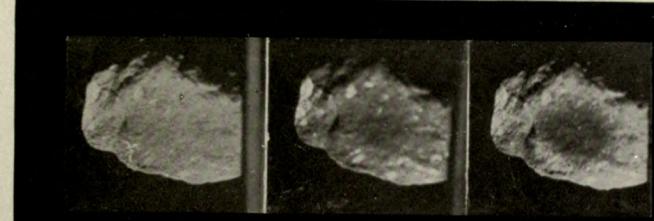
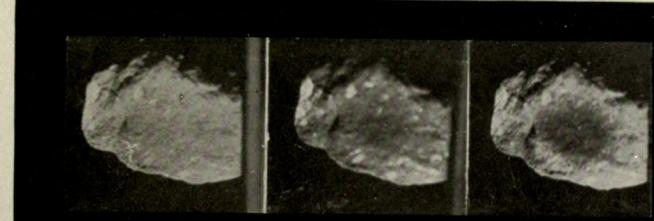
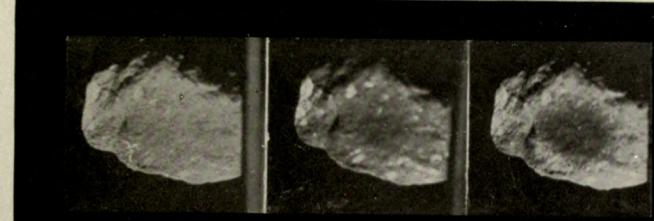
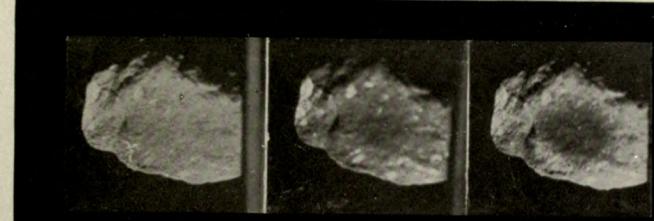
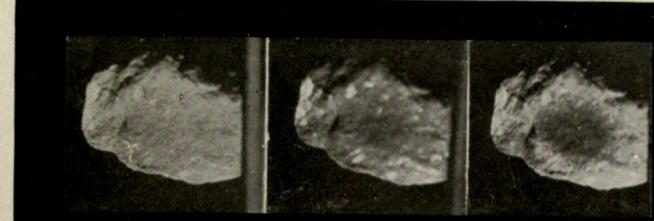
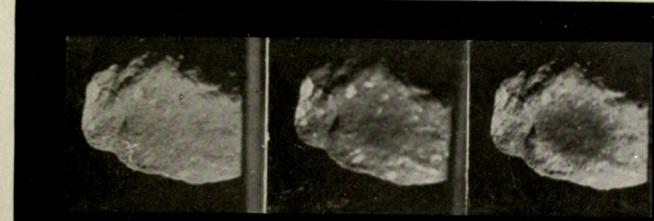
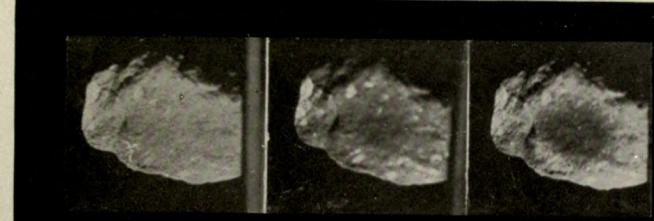
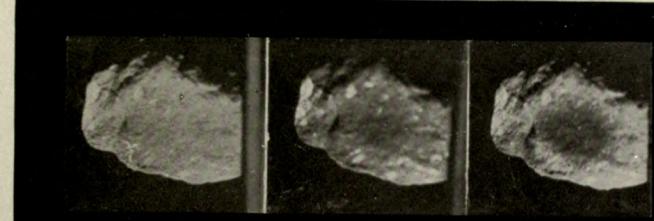
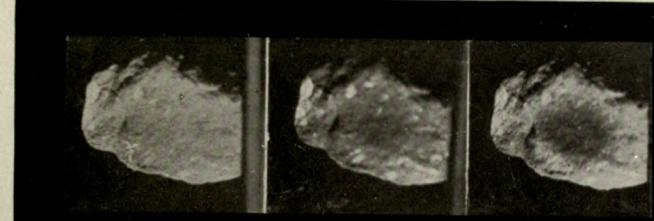
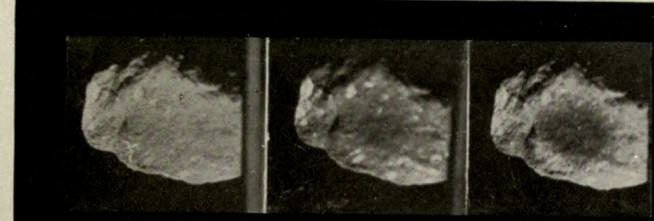
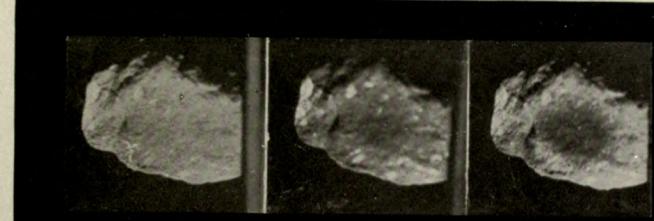
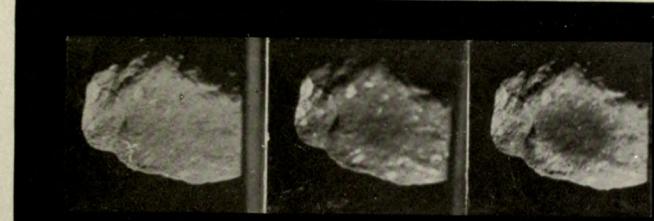
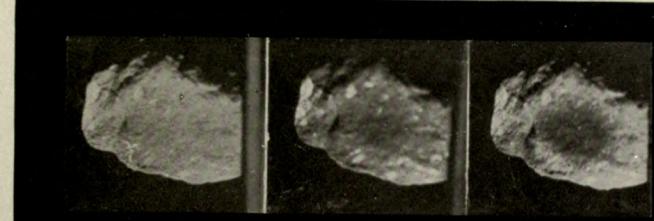
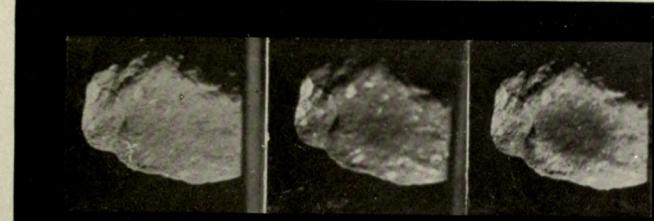
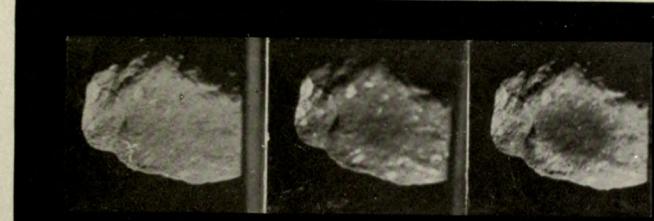
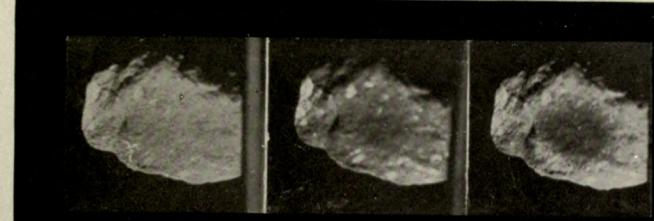
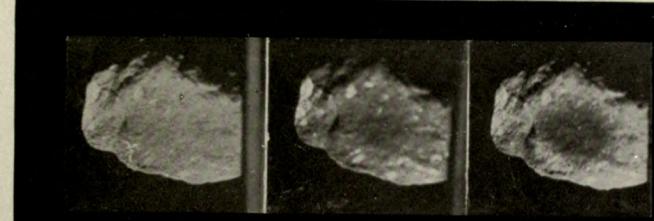
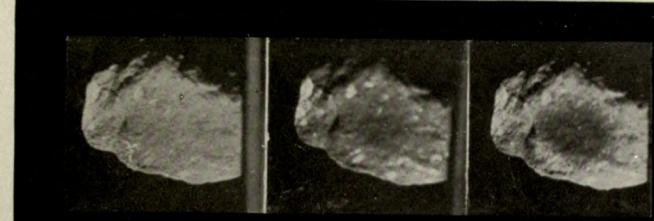
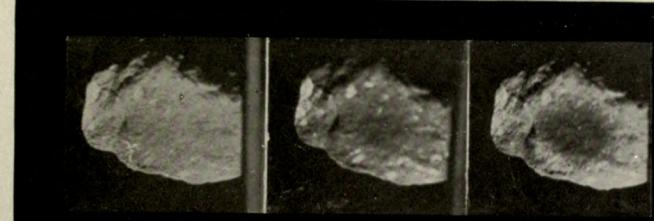
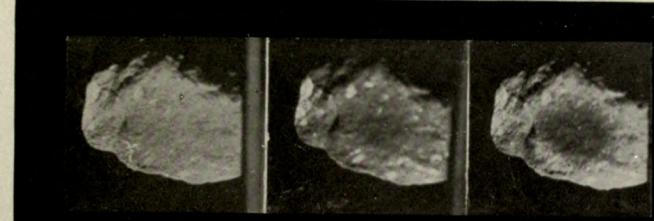
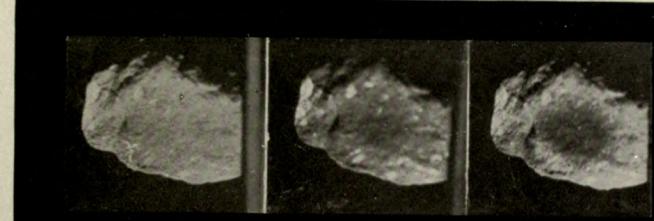
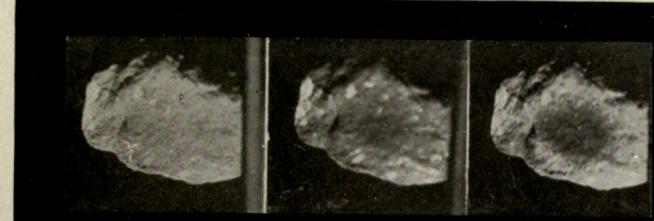
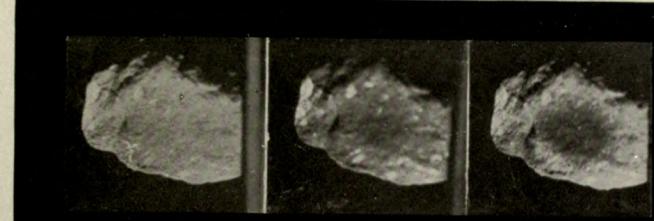
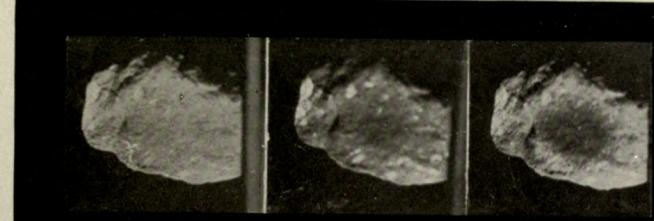
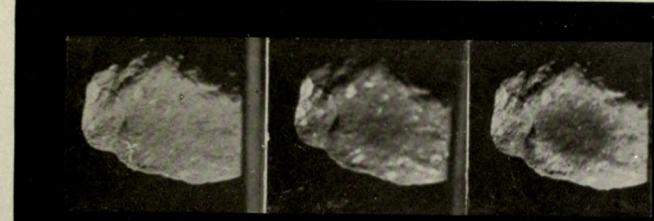
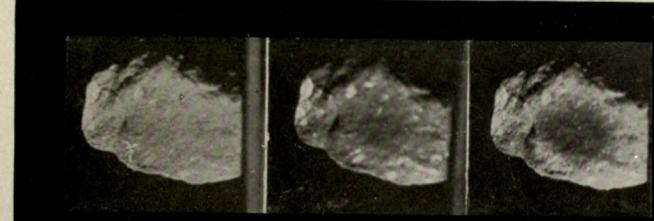
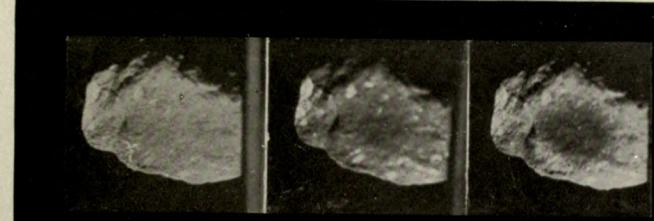
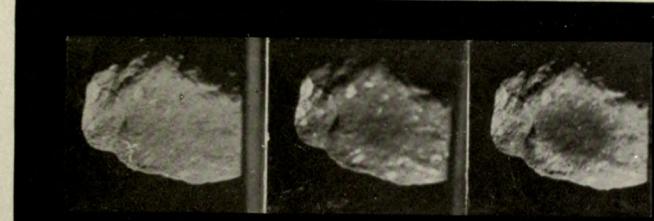
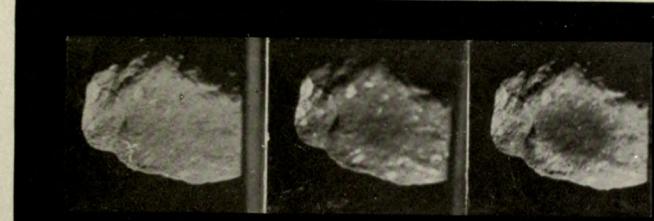
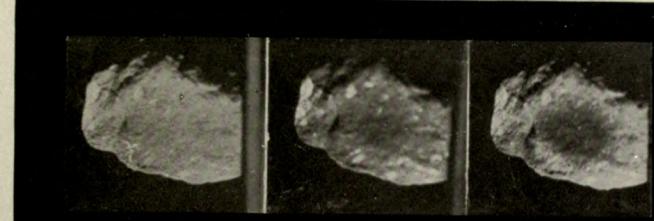
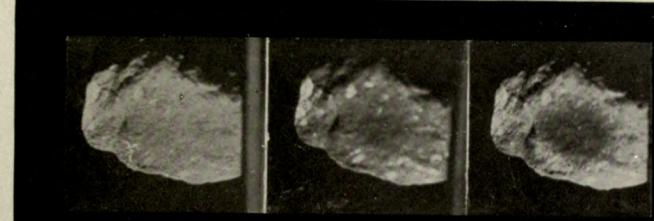
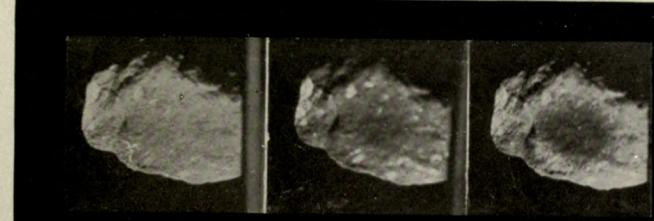
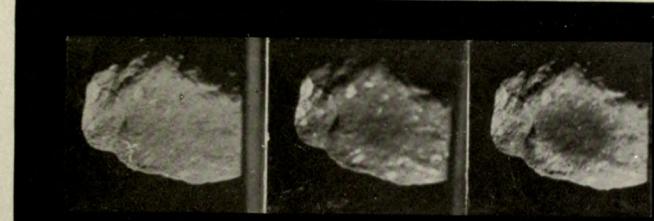
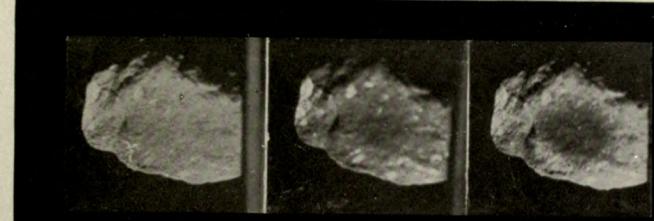
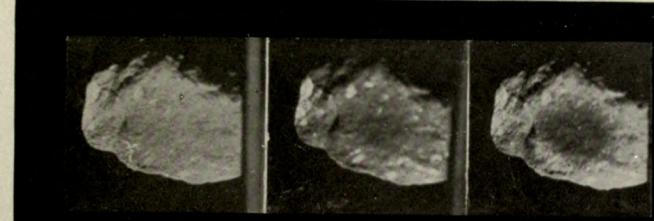
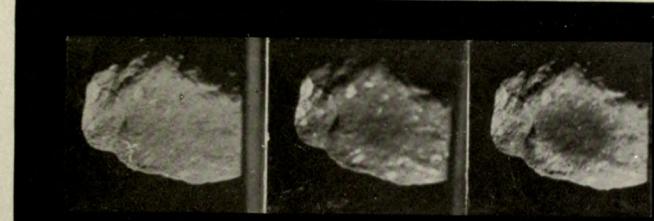
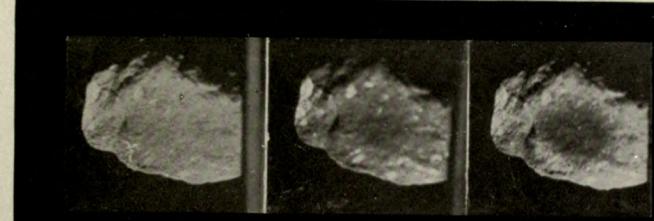
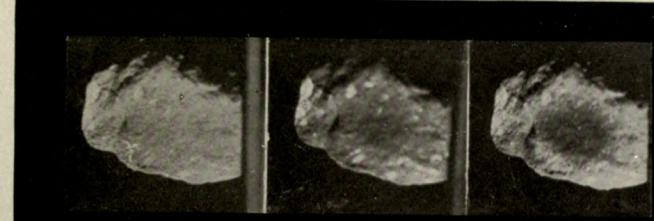
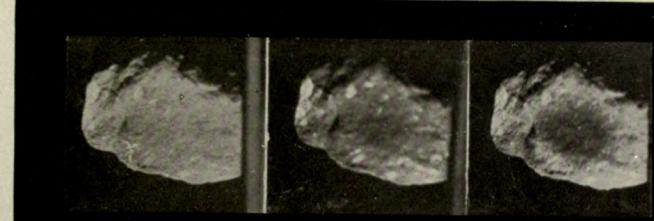
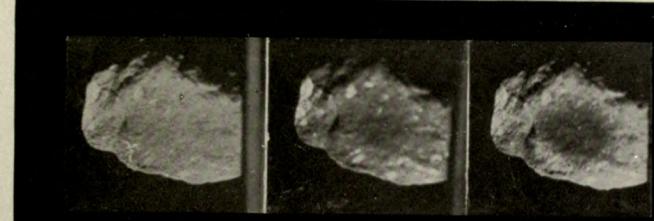
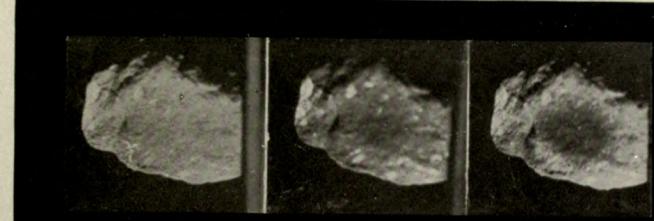
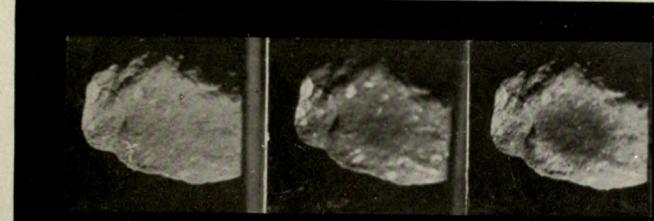
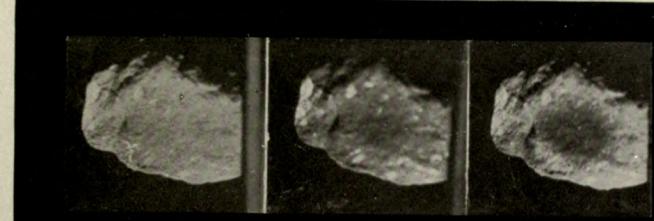
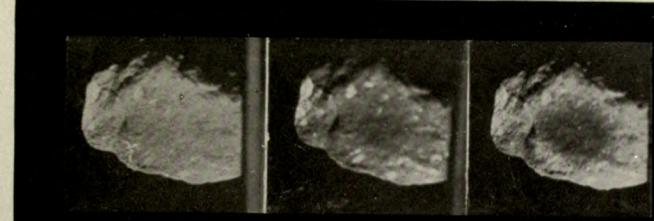
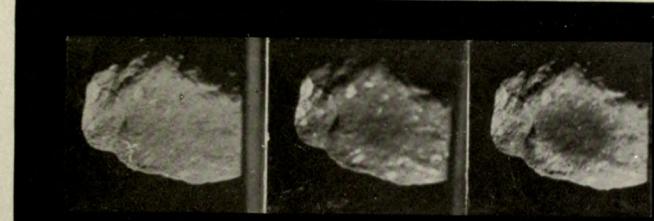
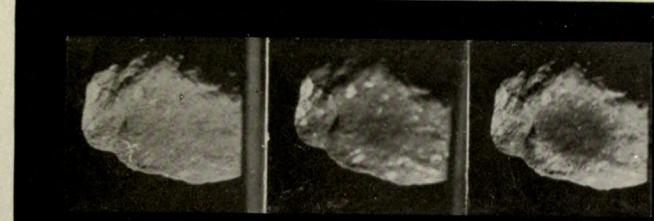
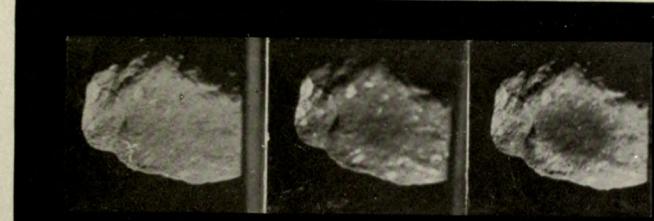
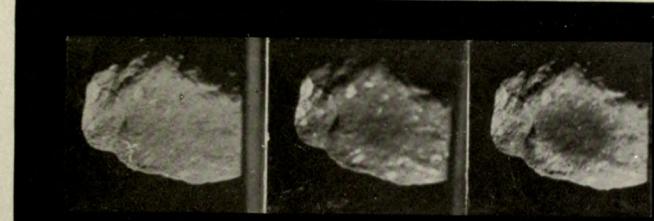
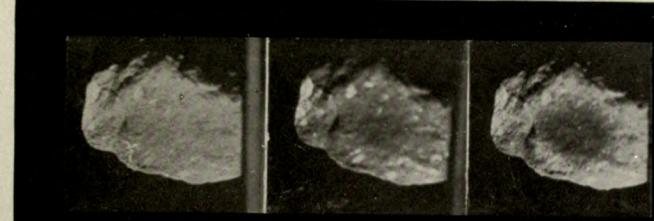
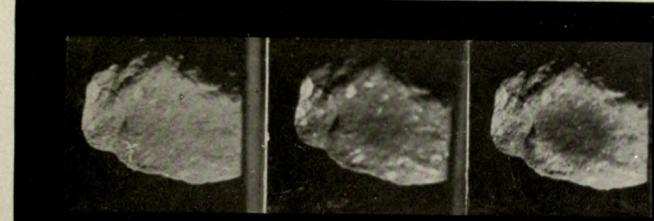
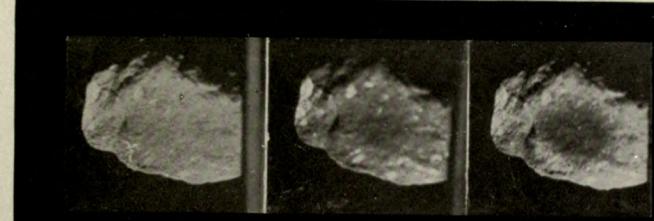
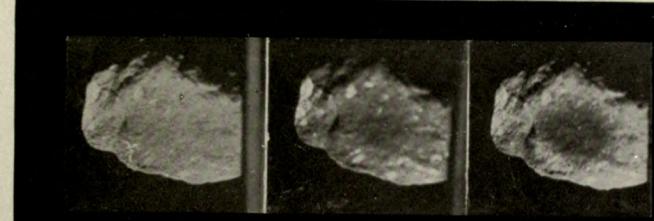
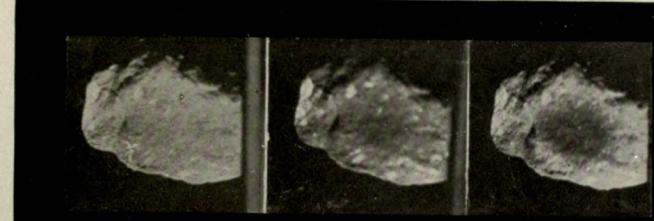
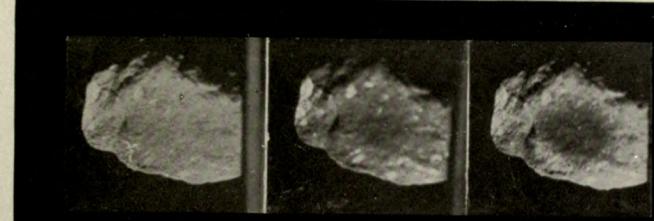
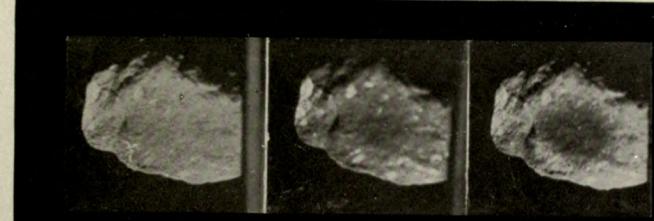
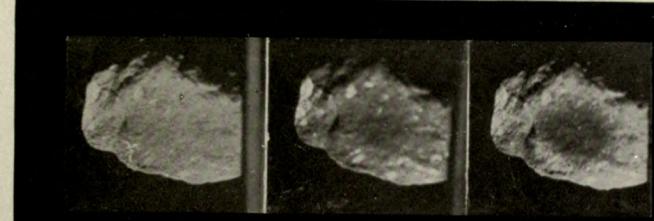
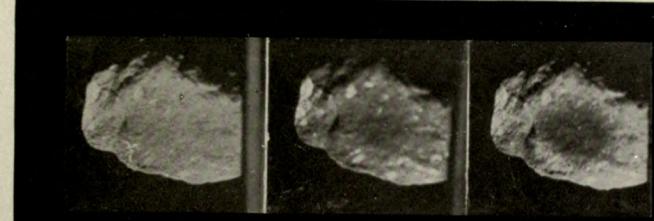
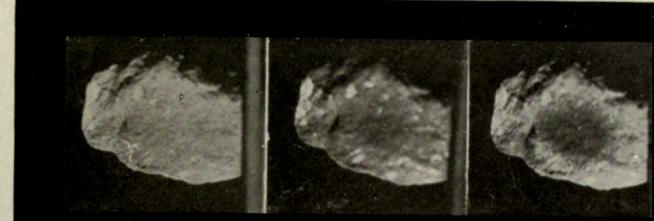
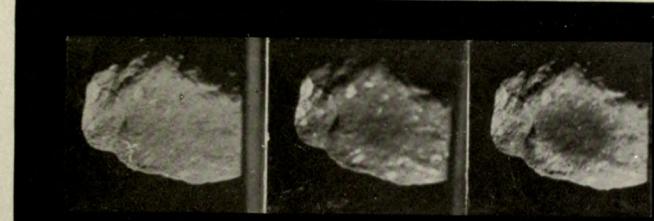
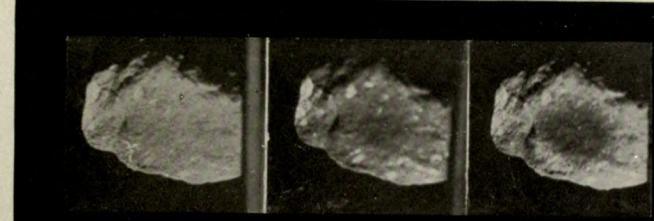
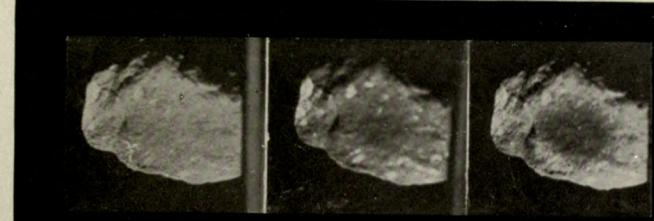
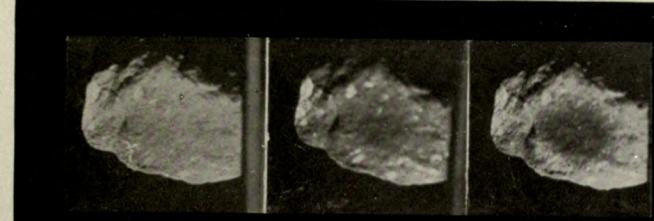
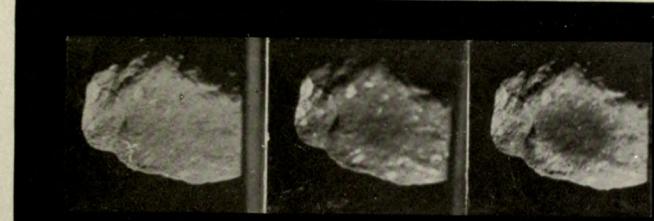
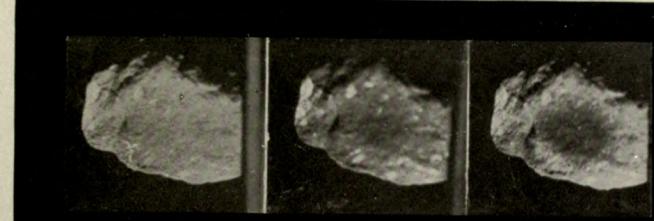
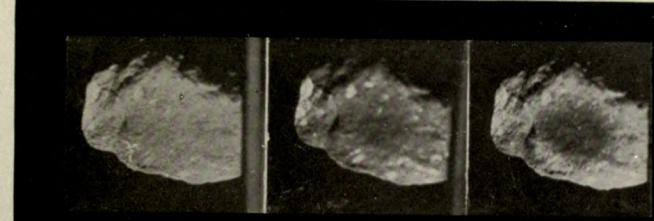
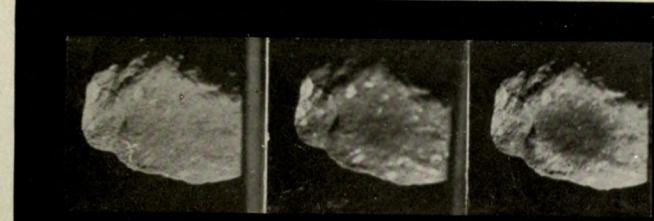
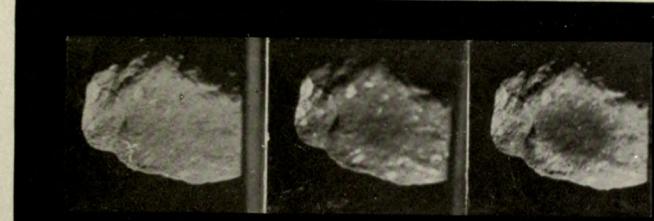
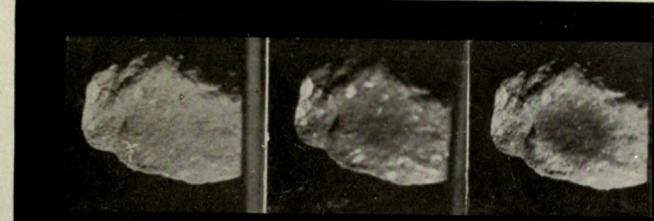
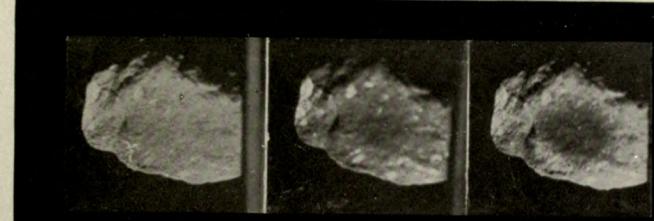
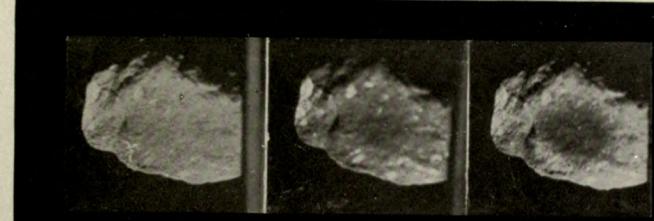
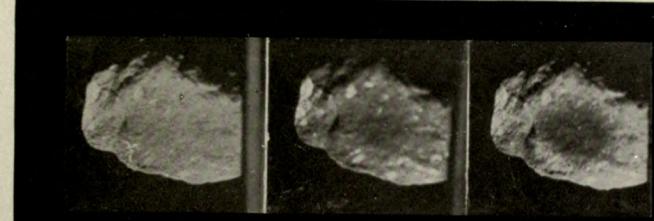
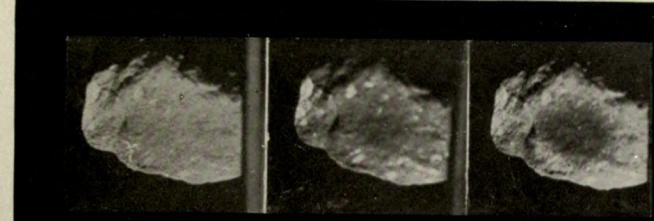
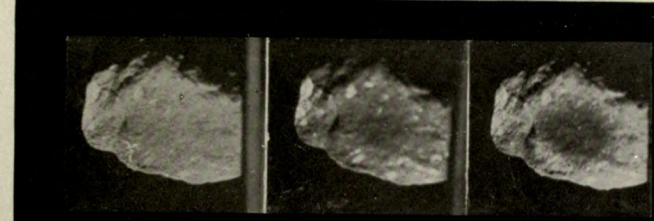
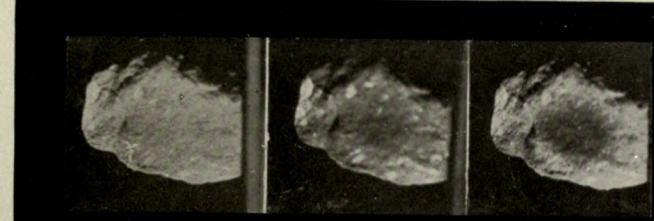
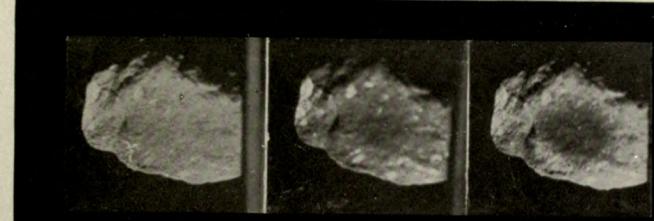
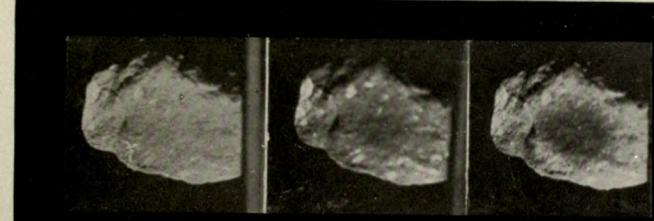
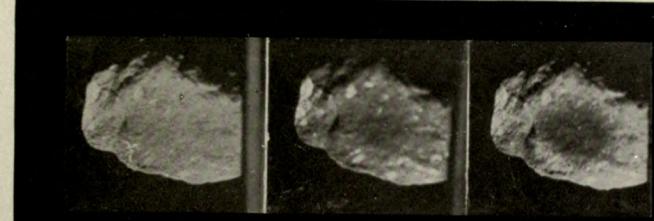
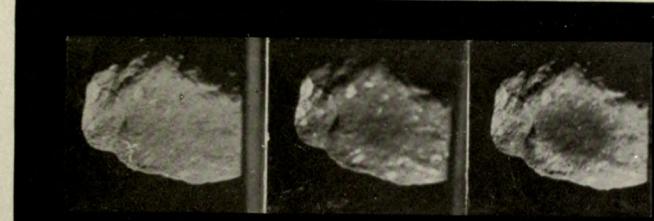
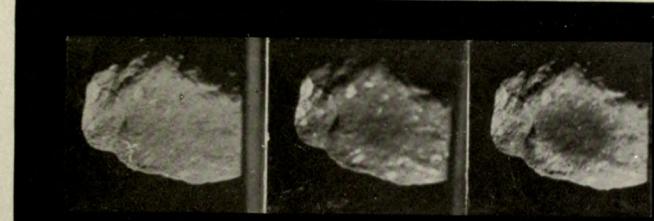
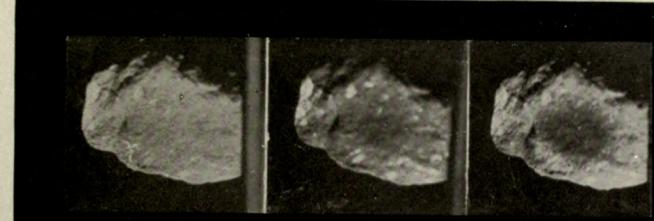
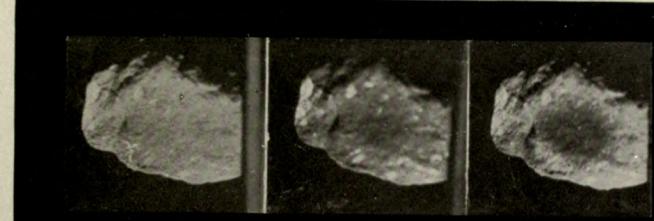
Ultra-violet



Ultra-Violet



Yellow



DESCRIPTION OF PLATE 10.

ILLUSTRATING PAPER ON THE SATELLITES OF THE MERCURY LINES.

The structure of the two yellow and the green mercury lines, photographed in the fourth order spectrum of the 40 foot spectrograph. The violet line 4358 photographed in the fifth order.

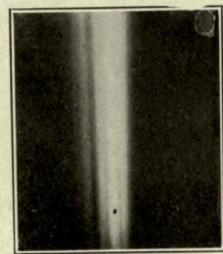


FIG. 1. $\lambda = 5769$.

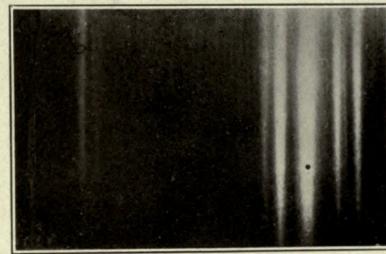


FIG. 2. $\lambda = 5790$.

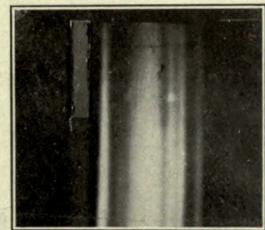


FIG. 3. $\lambda = 5461$.

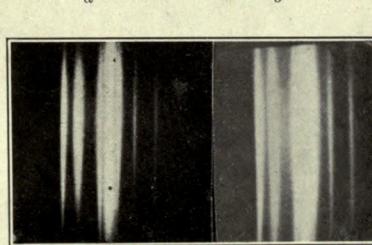


FIG. 4. $\lambda = 4358$.
PLATE 10

UNIVERSITY OF CALIFORNIA LIBRARY
BERKELEY

QC356

W62

Return to desk from which borrowed.
This book is DUE on the last date stamped below. V.1

-387

PHYSICS LIBRARY

DEC 10 1959

NOV 20 1975

LD 21-100m-11,49(B7146s16)476



CO32785892

